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INFRASOUND AND THE INFRASONIC MONITORING OF ATMOSPHERIC NUCLEAR EXPLOSIONS:

Past Monitoring Efforts

J. Michael McKisic

Tracor Applied Sciences, Inc.
1601 Research Boulevard
Rockville, MD 20850-3173

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This technical report has been reviewed and is approved for publication.

Delaine Reiter
DELAINE R. REITER
Contract Manager
Earth Sciences Division

James F. Lewkowicz
JAMES F. LEWKOWICZ
Director
Earth Sciences Division

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1601 Research Boulevard
Rockville, MD 20850-3171

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In brief, the U.S. monitored virtually all atmospheric nuclear explosions conducted by China, France, the former Soviet Union and the United States. The first nuclear explosion to be infrasonically monitored was the 21 KT air-dropped Able test which was conducted at the Bikini test site in the south-Pacific on June 30, 1946, and the last nuclear explosion which was infrasonically monitored was the 3 MT Chinese test which occurred on November 17, 1976.

The review of the detection performance of continental stations used to monitor U.S. tests at the NTS indicates that maximum detection ranges for explosions of ~ 1 KT can vary from 1350 km to 3585 km depending on the noise levels at a particular station and on the environmental conditions along the propagation path. In addition, recent work utilizing still classified data acquired during the existence of the USAEDS infrasound program as well as other independent estimates is discussed which indicates that a proposed 60 station infrasound network can ensure detection of a 1 KT atmospheric test with a location uncertainty of 100 km over most of the earth.

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ABSTRACT

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Although there was apparently no single overall monitoring program *per se*, it is, nevertheless, convenient to think of the work which was conducted as being accomplished in three programs: (1) the monitoring of foreign nuclear explosions at significant range from the various test sites; (2) the monitoring of U.S. nuclear tests at long ranges from the NTS (National Test Site) and (3) the monitoring of U.S. tests at the NTS at short ranges: typically < 270 km. The long range monitoring program was conducted under a program accorded the acronym: USAEDS (U.S. Atomic Energy Detection System).

All three of the programs were based on the use of a number of distributed monitoring stations and those associated with long range monitoring were typically equipped with an array of four very sensitive microbarograph sensors. Because some of the station locations which were utilized in the monitoring of foreign tests remain classified, no discussion of this aspect of the U.S. monitoring program is discussed herein except to note that the network performance was deemed to be quite good.

The review of the detection performance of continental stations used to monitor U.S. tests at the NTS indicates that maximum detection ranges for explosions of ~ 1 KT can vary from 1350 km to 3585 km depending on the noise levels at a particular station and on the environmental conditions along the propagation path.

In addition, recent work utilizing still classified data acquired during the existence USAEDS infrasound program [*Clauter and Blandford*, 1996] as well as other independent estimates [*Christie*, 1995] is discussed which indicates that a proposed 60 station infrasound network can ensure detection of a 1 KT atmospheric test with a location uncertainty of 100 km over most of the earth. Because of low station density in the southern hemisphere, it will likely prove necessary to augment the currently planned 4-element arrays with additional sensors to increase array gain for a number of southern hemisphere stations.

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The author would like to express his sincere appreciation to Dr. Robert Blandford of AFTAC for suggesting this work and to Ms. Leslie Casey of the DOE for her support and encouragement during its conduct. Special appreciation is due Dr. Dean Clauter of AFTAC for the provision of a significant amount of data, for numerous informative conversations and for most graciously allowing the incorporation of his and Dr. Blandford's network modeling results into the main body of this report prior to their publication at the Fall 1996 Meeting of the American Geophysical Union.

1.0 INTRODUCTION

This report presents an overview and discussion of past U.S. efforts which were directed toward the infrasonic monitoring of atmospheric nuclear explosions. The report is one of four resulting from a DOE (Department of Energy) sponsored seventeen month investigation and review of past work in infrasound. Other project related reports include: an annotated bibliography of selected papers in infrasound [*McKisic* (1996a)]; a collection of relevant environmental data involving northern and southern hemispheric temperature, wind speed and cloud cover data [*McKisic* (1996b)]; and a comprehensive literature review on infrasound and infrasonic monitoring [*McKisic* (1997)]. The report is focused on a discussion of only low-yield (< 4KT) tests which are of current concern to the monitoring of a CTBT (Comprehensive Test Ban Treaty).

In brief, the U.S. monitored virtually all atmospheric nuclear explosions conducted by China, France, the former Soviet Union and the United States. The first nuclear explosion to be infrasonically monitored was the 21 KT air-dropped Able test which was conducted at the Bikini test site in the south-Pacific on June 30, 1946 [*DOE*, 1994], and the last nuclear explosion which was infrasonically monitored was the 3 MT Chinese test which occurred on November 17, 1976.

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the U.S. monitoring program is discussed herein except to note that the network performance was deemed to be quite good.

The programs involved with the long range monitoring of foreign and U.S. atmospheric nuclear explosions was given the name, U.S. AEDS (Atomic Energy Detection System) or USAEDS, and was conceived following World War II when it became clear that nations other than the U.S. would one day develop a nuclear capability and that U.S. national security dictated monitoring such efforts. As pointed out by [*AFTAC*, 1992], the "USAEDS came into being when General Dwight D. Eisenhower Army Chief of Staff, directed General Carl A. Spaatz, Commanding General of the Air Force Corps, to 'assume responsibility for detecting atomic explosions anywhere in the world'."

The basic period of operation of the USAEDS appears to have covered the time period extending from 1948 to 1975 when the system was largely dismantled, although the two 21 KT U.S. air-dropped tests at Bikini Atoll in 1946 were also evidently acoustically monitored. The acoustic monitoring of the very early U.S. atmospheric tests conducted through 1950 presumably utilized conventional low-frequency microphones with all further tests monitored using microphones equipped with Daniels pipe front end noise reducers.

The U.S. Army Signal Corps first operated the acoustic stations which began sending acoustic reports to AFTAC (Air Force Tactical Operations Center) on a regular basis beginning on September 1, 1948. In 1969, operation of the USAEDS system was transferred to AFTAC. During the time period extending from 1951 through 1961 the USAEDS typically involved the utilization of at least 15 relatively fixed stations as well as stations operated on the west coast of the U.S. at various locations by the NEL (Naval Electronics Laboratory) and on the east coast of the U.S. by the NBS (National Bureau of Standards) at Washington, DC and by the AFCRL (Air Force Cambridge Research Laboratories) at Boston, MA.

Unlike the component of USAEDS involved with the monitoring of foreign nuclear explosions, the two programs which were involved in monitoring U.S. atmospheric tests can be discussed in some detail as only the locations of two of the long range stations which were utilized remain classified or "highly sensitive".

For purposes of exposition, the remainder of the report is divided into four sections. Section 2.0, Subsection 2.1, presents a discussion of results from the program involved with the long-range monitoring of U.S. tests at the NTS where the low-yield tests of current interest were conducted. In addition to indicating network performance, a discussion and description of the instrumentation used is also presented and tables of noise data are provided to illustrate the fluctuations in noise levels as a function of time.

Section 2.0, Subsection 2.2, briefly discusses the short range monitoring effort which was conducted by the Sandia National Laboratory and, as pointed out by *Reed* (1996), was entirely separate and distinct from the long range monitoring programs. Section 3.0 provides two assessments of infrasonic monitoring capability based on analyses of all stations used in the long range monitoring of U.S. and foreign nuclear explosions. The first is based on an analysis of 781 nuclear explosions, involves the use of logit and maximum-likelihood models and derives probability of detection as a function of explosive yield and source-to-receiver range [*Nicholson*, 1995]. The second assessment utilizes network modeling software developed for seismic monitoring ("NETSIM") in conjunction with empirically derived pressure-range and station-noise curves, and an assumed probability of detection model [*Clauter and Blandford*, 1966]. Results are presented for magnitude-probability and radius of uncertainty contours for a proposed 60 station infrasonic monitoring network. Section 4.0 presents a brief discussion of results and provides a short account of the inception of the VELA program. Section 5.0 provides a listing of the references cited in the body of the report.

2.0 THE INFRASONIC MONITORING OF U.S. ATMOSPHERIC NUCLEAR EXPLOSIONS

2.1. Monitoring at Long Ranges

During the time period extending from June 30, 1946 until November 4, 1962, the U.S. conducted 210 atmospheric and 5 underwater nuclear tests. Except for the TRINITY explosion on July 16, 1945 and the bombs dropped on Hiroshima on August 5, 1945 and on Nagasaki on August 9, 1945, all U.S. atmospheric explosions were monitored by a number of infrasonic monitoring stations. Those explosions having yields of 4 KT and below are indicated in Table 1 [*DOE*, 1994].

The infrasonic monitoring of U.S. atmospheric nuclear explosions was conducted by three agencies: the U.S. Navy NEL (Naval Electronics Laboratory) in San Diego, California, the U.S. Army SCEL (Signal Corps Engineering Laboratories) and by the NBS (National Bureau of Standards) in Washington D.C. Typically, 18 stations were involved in the monitoring but the number evidently varied from test to test. Table 2 provides a geographical listing of sixteen unclassified infrasonic monitoring stations and the responsible agency for each station. Figure 1 provides a geographical map of some station locations and distances from the NTS site.

As of this writing, most of what has been reconstructed with respect to U.S. monitoring of U.S. Tests is derived from five recently declassified "WT" reports: OPERATIONS BUSTER AND JANGLE (1952a); OPERATION TUMBLER-SNAPPER (1952b); OPERATION IVY (1953); OPERATION UPSHOT-KNOTHOLE (1954) and OPERATION CASTLE (1955). Inspection of Table 1 shows that there were 6 explosions in these test series having yields below 4 kT.

Instrument descriptions are provided in three appendices to the BUSTER & JANGLE "WT" report [*Olmsted*, 1952a]. In particular, the NEL (Naval Electronics Laboratory) participation is described in Appendix A by *McLoughlin and Johnson* (1951),

Table 1. Test/Series event, date, location, altitude, purpose and yield of all U.S. atmospheric nuclear explosions having yields less than or equal to 4 KT. In the table, WR indicates that the test was weapons related, SE that the test was a safety experiment and WE that the test was for weapons effect studies. [Data adopted from *DOE* (1994).]

Test Series/Event	Date	Location	Altitude	Purpose	Yield (KT)
OPERATION RANGER					
Able	1/27/51	NTS	Airdrop	WR	1.0
Easy	2/1/51	NTS	Airdrop	WR	1.0
OPERATION JANGLE					
Sugar	11/19/51	NTS	Surface	WE	1.2
Uncle	11/29/51	NTS	Crater	WE	1.2
OPERATION TUMBLER-SNAPPER					
Able	4/1/52	NTS	Airdrop	WE	1.0
Baker	4/15/52	NTS	Airdrop	WE	1.0
OPERATION UPSHOT KNOTHOLE					
Ruth	3/31/53	NTS	Tower	WR	0.2
Ray	4/11/53	NTS	Tower	WR	0.2
OPERATION TEAPOT					
Wasp	2/18/55	NTS	Airdrop	WE	1.0
Moth	2/22/55	NTS	Tower	WR	2.0
Hornet	3/12/55	NTS	Tower	WR	4.0
Ess	3/23/55	NTS	Crater	WR	1.0
Wasp Prime	3/29/55	NTS	Airdrop	WR	3.0
HA	4/6/55	NTS	Airdrop	WR	3.0
Post	4/9/55	NTS	Tower	WR	2.0

Table 1 (Cont.). Test/Series event, date, location, altitude, purpose and yield of all U.S. atmospheric nuclear explosions having yields less than or equal to 4 KT. In the table, WR indicates that the test was weapons related, SE that the test was a safety experiment and WE that the test was for weapons effect studies. [Data adopted from *DOE* (1994).]

OPERATION REDWING					
Yuma	5/27/56	Enewetok	Tower	WR	0.190
Kickapoo	6/13/56	Enewetok	Tower	WR	1.49
Osage	6/16/56	Enewetok	TowerAirdrop	WR	1.70
OPERATION PLUMBBOB					
Franklin	6/2/57	NTS	Tower	WR	0.140
Lassen	6/5/57	NTS	Tower	WR	5×10^4
John	7/19/57	NTS	Rocket	WR	~2.0
Wheeler	9/6/57	NTS	Balloon	WR	0.197
Coulomb-B	9/6/57	NTS	Surface	SE	0.300
Laplace	9/8/57	NTS	Balloon	WR	1.0
OPERATION PROJECT 58A					
Coulomb-C	12/9/57	NTS	Surface	SE	0.5
OPERATION HARDTACK 1					
Yucca	4/28/58	Pacific	Balloon	WE	1.7
OPERATION ARGUS					
Argus I	8/28/58	South Atlantic	Rocket	WE	1.0 - 2.0
Argus II	8/30/58	South Atlantic	Rocket	WE	1.0 - 2.0
Argus III	9/6/58	South Atlantic	Rocket	WE	1.0 - 2.0

Table 1 (Cont.) Test/Series event, date, location, altitude, purpose and yield of all U.S. atmospheric nuclear explosions having yields less than or equal to 4 KT. In the table, WR indicates that the test was weapons related, SE that the test was a safety experiment and WE that the test was for weapons effect studies. [Data adopted from *DOE* (1994).]

OPERATION HARDTACK II

Mora	9/29/58	NTS	Balloon	WR	2.0
Hidalgo	10/5/58	NTS	Balloon	SE	0.077
Lea	10/13/58	NTS	Balloon	WR	1.4
Dona Ana	10/16/58	NTS	Balloon	WR	0.037
Vesta	10/17/58	NTS	Surface	SE	0.024
Rio Arriba	10/18/58	NTS	Tower	WR	0.090
Wrangell	10/22/58	NTS	Balloon	WR	0.115
Rushmore	10/22/58	NTS	Balloon	WR	0.188
Catron	10/24/58	NTS	Tower	SE	0.021
Juno	10/24/58	NTS	Surface	SE	0.0017
Ceres	10/26/58	NTS	Tower	SE	7×10^{-4}

OPERATION HARDTACK II (Cont.)

De Baca	10/26/58	NTS	Balloon	WR	2.2
Chauvez	10/27/58	NTS	Tower	SE	6×10^{-4}
Humboldt	10/29/58	NTS	Tower	WR	0.0078
Santa Fe	10/30/58	NTS	Balloon	WR	1.3
Titania	10/30/58	NTS	Tower	SE	2×10^{-4}

OPERATION DOMINIC

Tanana	5/25/62	XMAS Island	Airdrop	WR	2.6
Petit	6/19/62	XMAS Island	Airdrop	WR	2.2

Table 2. Locations of infrasonic stations used to monitor U.S. atmospheric nuclear explosions conducted at the NTS (National Test Site). The azimuth is in degrees clockwise as measured from true north and the distance is in km. NEL designates the Navy Electronics Laboratory, SCEL designates the Army Signal Corps Engineering Laboratories and NBS designates the National Bureau of Standards. The indicated distances are measured on a great circle path extending from the station position to NTS. The last column indicates which stations participated in the BUSTER and JANGLE (J), TUMBLER-SNAPPER (T-S) and UPSHOT-KNOTHOLE (U-K) test series. [Data taken from *Olmsted and Nowak,* (1954).]

Agency	Station	Location (Latitude/Longitude)		Azimuth (Deg)	Distance (km)	Tests
NEL	Los Angeles, CA	34° 07'N	118° 17'W	034	380	U-K
NEL	San Diego, CA	32° 49'N	117° 15'W	013	475	J, U-K
NEL	Dateland, AZ	32° 53'N	113° 15'W	337	505	U-K
NEL	Gila Bend, AZ	32° 52'N	112° 40'W	328	530	U-K
SCEL	Ft. Lewis, WA	47° 05'N	122° 35'W	152	1230	J, T-S, U-K
SCEL	Pyote AFB, TX	31° 30'N	103° 15'W	301	1350	J, T-S, U-K
NEL	Eagle Mt. Lake,TX	32° 53'N	097° 30'W	290	1755	J
SCEL	Barksdale AFB, LA	32° 30'N	093° 45'W	290	2080	U-K
SCEL	Breckinridge, KY	38° 00'N	088° 00'W	278	2460	J, T-S
NEL	Eglin AFB, FL	30° 30'N	086° 35'W	293	2818	J
NBS	Washington, DC	38° 57'N	077° 04'W	279	3400	J, T-S, U-K
SCEL	Belmar, NJ	40° 12'N	074° 05'W	278	3585	J, T-S, U-K
SCEL	Fairbanks, AL	64° 50'N	147° 40'W	131	3710	J, T-S, U-K
SCEL	Oahu, HI	21° 31'N	158° 05'W	057	4375	J, T-S, U-K
SCEL	Thule, Greenland	76° 32'N	068° 40'W	237	5000	U-K
SCEL	Hanau, Germany	50° o7'N	006° 59'E	318	8900	U-K

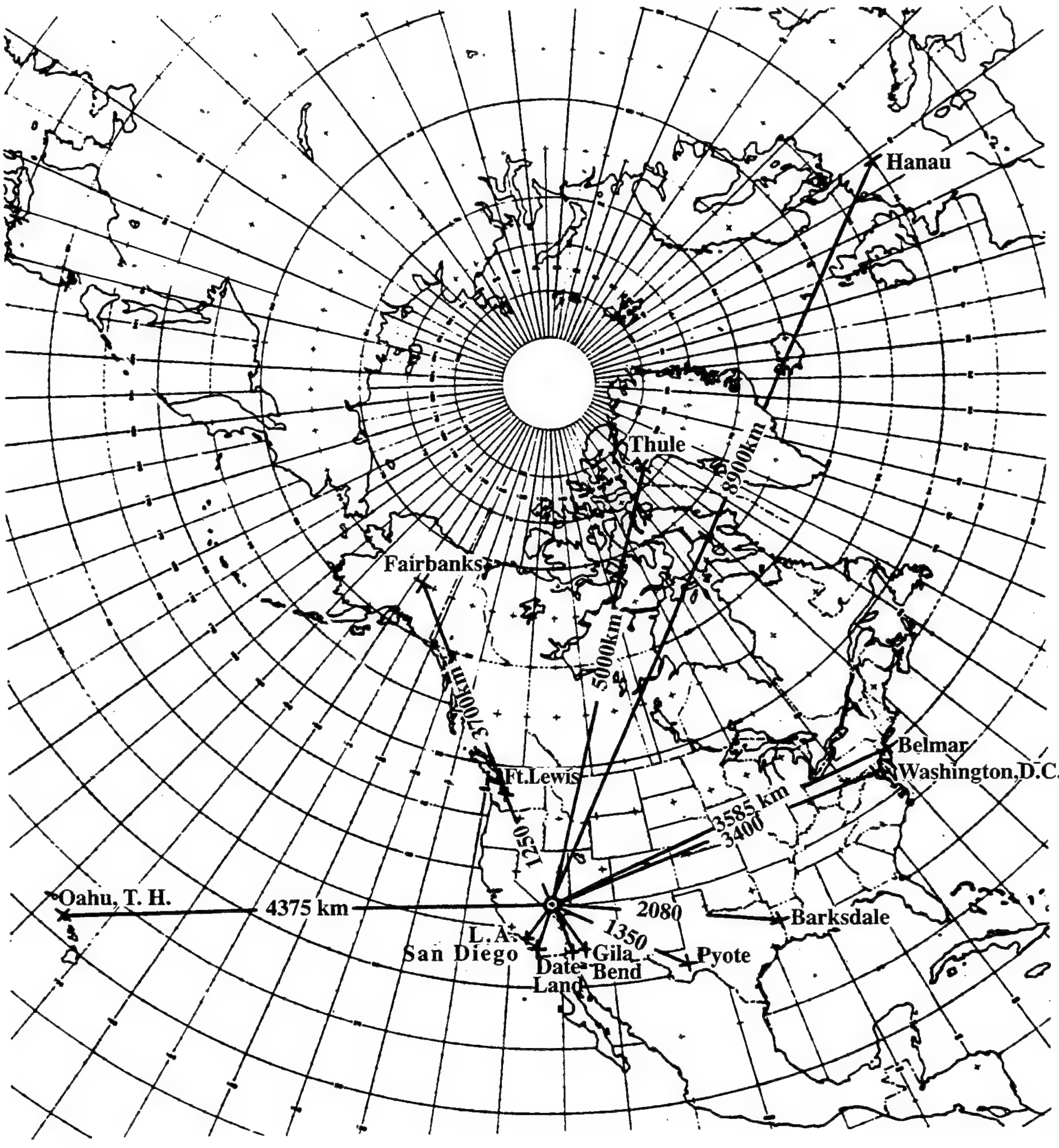


Figure 1. Geographical locations and distances of 14 infrasonic array stations from the NTS. [Figure adopted from the OPERATION UPSHOT-KNOTHOLE station deployment [*Olmsted and Nowak* (1954)] .

the Army Signal Corps participation is described in Appendix B by *Crenshaw, Lonnie and Pressman* (1952) and the NBS (National Bureau of Standards) participation is described in Appendix C by *Chrzanowski, et al.*, (1952).

The NEL participation involved the occupation of four sites: Oahu, HI; Eglin AFB, FL; Eagle Mountain Lake, TX; and San Diego, CA. The Texas and Florida recording stations used four element arrays each element of which was made up of a low-frequency Rieber microphone connected to a 1,000' tapered Daniel's pipe array designed by the Army Signal Corps. The sensors making up each of the arrays were deployed in a quadralateral pattern as illustrated for the case of the array at Eagle Mt. Lake, TX in Figure 2.

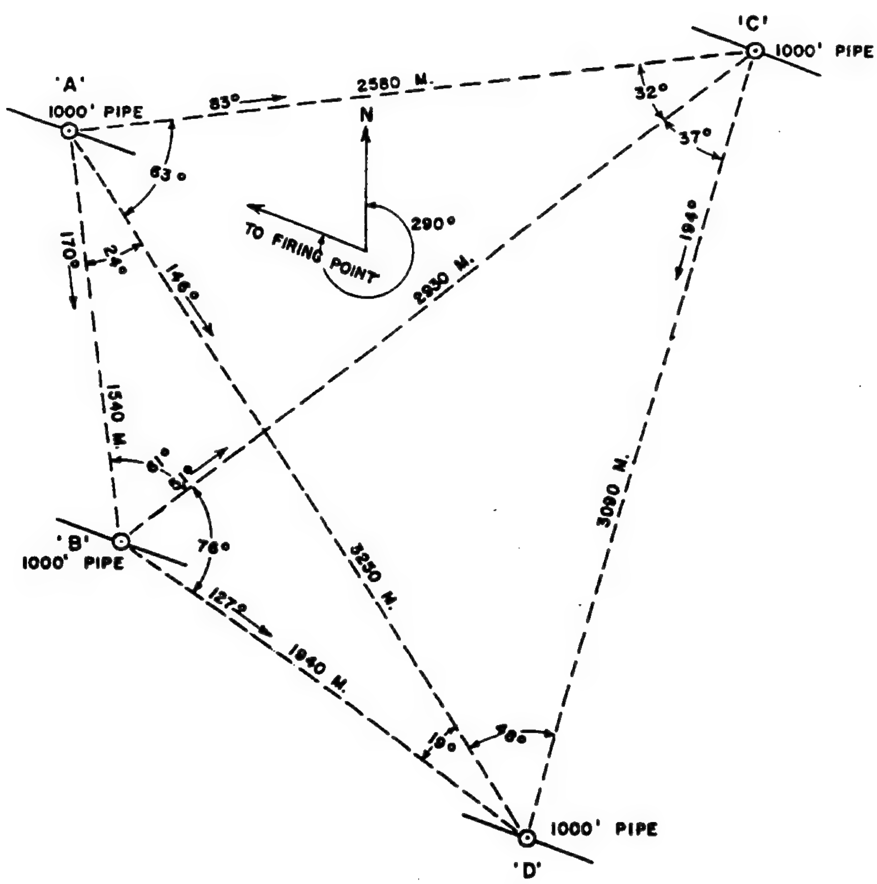


Figure 2. The infrasonic microphone deployment for the NEL station at Eagle Mountain Lake, Texas during the BUSTER & JANGLE test series.

The monitoring at the San Diego station was described as performed "on an unofficial basis" and only two microphones were available. The NEL and the NBS were "guests" at the Oahu, HI site and simply attached their recording instruments to the four element array which had been installed by the Army Signal Corps.

The Army Signal Corps participation also involved the occupation of four sites: Pyote, TX; Camp Breckinridge, KY; Belmar, NJ; and Oahu, HI. Each site consisted of a single four element sensor array with each element consisting of a condenser microphone equipped with a noise reducing array of length 1740'. The array had 348 openings with a 5' spacing between each opening. This design was intended to reduce the background ambient noise by a factor of 18. The output of each sensor (microphone and pipe array) was connected by wire lines to a central processing station.

For the BUSTER & JANGLE test series "the microphone and the associated circuitry were modified to increase the response to periods as long as one minute. The response of the system to pressure variations in the infrasonic region has been determined experimentally and is illustrated in graphical form in Figure 3. A remotely controlled calibrator was also installed at each outpost emplacement (i.e., at each sensor location) to check the system performance, as required" [*Crenshaw, Lonnie and Pressman* (1952)].

The NBS participation in the BUSTER & JANGLE test series involved the occupation of three stations: Fort-Lewis-McChord AFB, WA; Oahu, HI and Washington, DC. The basic sensor utilized by the NBS is discussed in significant detail by *Chrzanowski, et al.*, (1952) and it is perhaps sufficient to simply provide a brief summary. In brief, the NBS developed two types of microphones of the capacitive diaphragm type which were referred to as either a "single-unit microphone" or a "ring-unit microphone". Each sensor type utilized the same capacitive pressure sensing element but different electronic oscillator circuits. In the single-unit microphone, the capacitive element functioned "as a variable condenser in the shunt of RC leg of a Wien bridge oscillator" whereas the ring-unit was designed for use as an element in a four element array of sensors

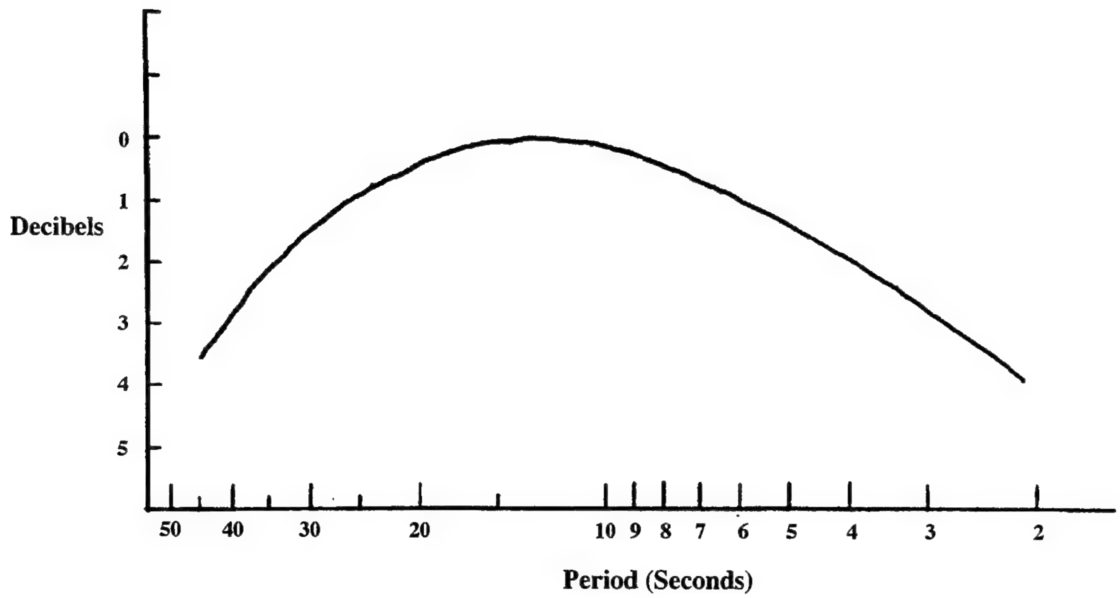


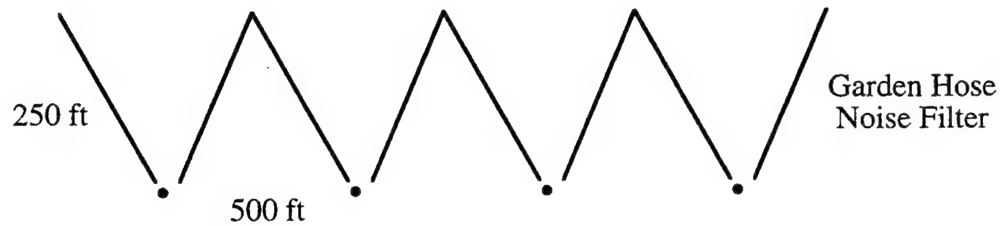
Figure 3. The frequency response of the improved infrasonic system M-2. [Figure adopted from *Crenshaw, Lonnie and Pressman* (1952).]

and, accordingly, the capacitive sensors "formed the variable capacitances in a four-section phase shift oscillator."

The two sensors were fronted by different noise reducers. In the case of the single-unit microphones, the 1000' pipe array developed by the Army Signal Corps was utilized. This type of array "was made up of pipe in 10' lengths tapering from 1.5" diameter at the center to 0.5" pipe at the ends. At 10' intervals, inlet plugs provided communication to the atmosphere. Three single-unit sensors were deployed at the NBS outside of Washington, DC.

The ring-microphones utilized noise reducing elements made up of 0.75" diameter garden hose with hypodermic needles of length 1.5" inserted along the length of the hose. The basic sensor arrangement is described as "a double W (WW)" with the microphone sections connected to the base of the W's". The straight lines composing the W's were about 250' long. "To give equal weight to each interval of the hose, the needles were spaced about 16 feet apart near the microphone cans and about 8 feet apart near the end of a 250' hose." Although no diagram was provided, the NBS configuration was evidently as

in Figure 4. For BUSTER & JANGLE, four single- and four ring-microphones were deployed at the Fort Lewis, WA station.



• Denotes Capacitive Sensing Element

Figure 4 The double-W ring-microphone arrangement used by the NBS in monitoring explosions from the BUSTER & JANGLE test series. The straight line segments are 250' lengths of garden hose and the capacitive sensing elements are located at the base of the W's. [Figure constructed based on a description provided by *Chrzanowski, et al.*, (1952).]

In OPERATION JANGLE, the Sugar event was a surface explosion and Uncle was a crater event indicating an explosion detonated just below the ground surface. The BUSTER and JANGLE test series of explosions took place over the time period from October 22, 1951 to November 29, 1951, eight stations were utilized and Table 3 summarizes the performance of the monitoring network for the two low yield 1.2 KT explosions. The station deployment for the test series is provided in Figure 5.

As indicated in Table 3, six stations detected the surface explosion and seven stations detected the underground event. The surface explosion was detected to a maximum range of 2818 km at Eglin AFB, Florida, and the underground test was detected to a maximum range of 3585 km at Belmar, New Jersey. The surface explosion was evidently not detected at the Washington, DC station (3400 km) and the Belmar, New Jersey station (3710 km) because of high noise levels at the time of signal reception: 13 μbar and 49 μbar, respectively. In addition, *Olmsted* (1952a) notes that the noise reducing arrays at the Belmar, New Jersey station were not of the optimum design.

Inspection of Table 3 clearly shows that propagation speeds are much higher to the east than to the west and it was hypothesized that this circumstance was due to westerly

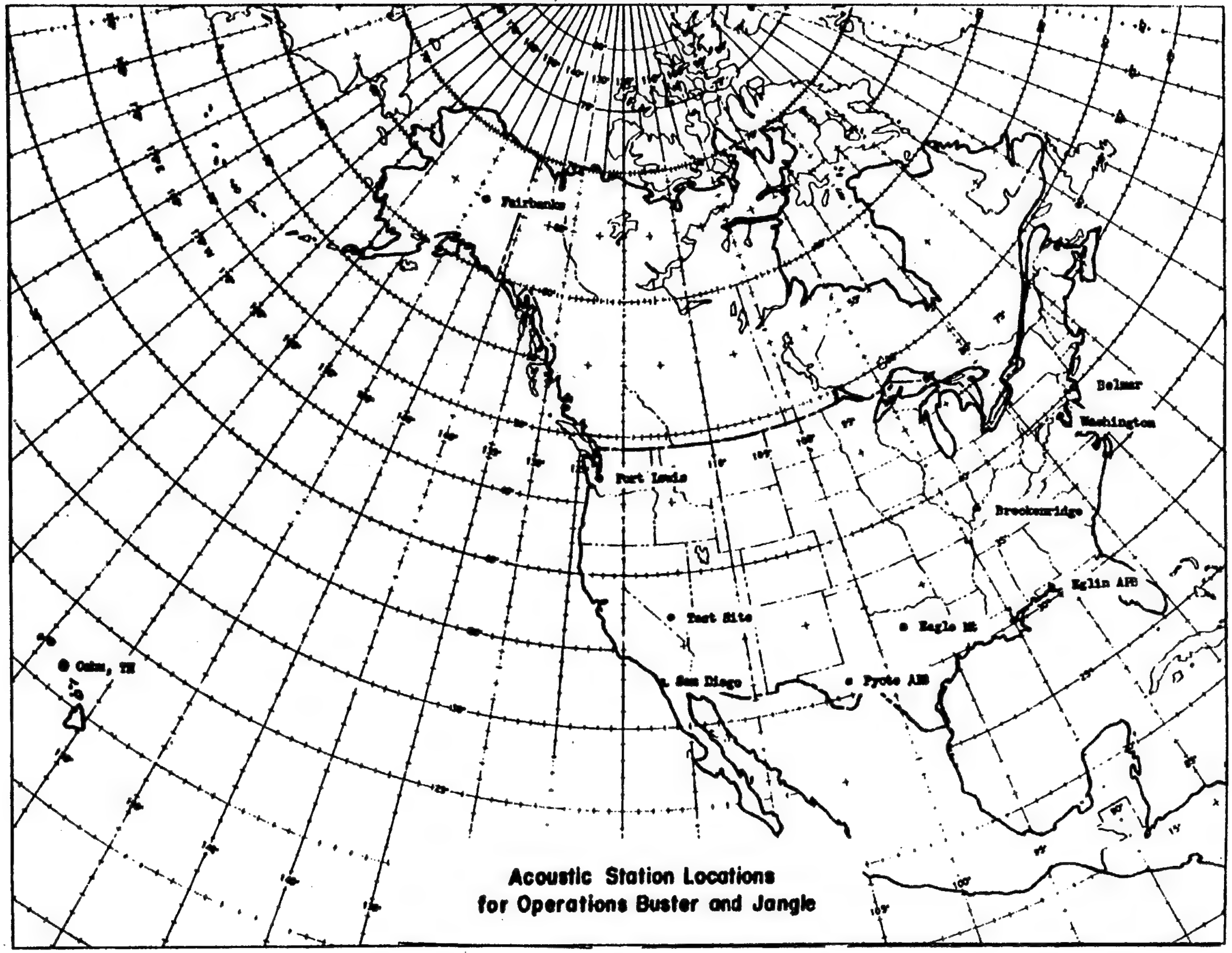


Figure 5. The U.S. infrasonic station locations for the operation BUSTER and JANGLE test series. [Figure adopted from *Olmsted* (1952).]

Table 3. Stations recording the 1.2 KT shots Sugar and Uncle in the JANGLE test series together with selected properties of the received waveforms. In the table, P-P denotes peak-to-peak amplitude. [Data adopted from *Olmsted* (1952).]

Station	Travel Speed (m/s)	Duration (min)	Max. P-P Signal Amplitude (μbar)	Avg. P-P Noise (μbar)	Signal Periods (s)	Measured Azimuth	Apparent Velocity (m/s)	Range (km)
Shot Sugar in the JANGLE Test Series: Yield 1.2 KT - 11/19/51								
San Diego, CA	284	8	17	4	1.5 - 6	--	--	505
Pyote AFB, TX	316	10	31	4	4,5,6,8,11	301.0°	346-381	1350
Ft. Lewis, WA	255	8	5	2	15-40	149.3°	374	1230
Eagle Mt. Lake, TX	312	10	12	2	3,5,7,10	290°	354	1355
Breckinridge, KY	302	6	15	6	5,6,7,8	271.8°	324-366	2460
Eglin AFB, FL	340	4.5	5	3	3-8,5	287°	365	2818
Shot Uncle in the JANGLE Test Series: Yield 1.2 KT - 11/29/51								
Pyote AFB, TX	346	17	23	6	3,4,5,6	302.0°	342-400	1350
Ft. Lewis, WA	258	3	6	3	15-40	145.4°	334	1230
Eagle Mt. Lake, TX	308	5.5	13	2	3-6	290°	360	1775
Breckinridge, KY	322	17	10	5	3,4,6,9	277.9°	312-383	2460
Eglin AFB, FL	307	10	10	3	4-7,5	288°	388	2818
Washington, DC	312	16	2.5	1	2,5,4,10	280°	388	3400
Belmar, N.J.	306	14	12	8	4,5,6,7	284.2°	331-348	3585

winds in the stratosphere. Figure 6 shows that this hypothesis was quite plausible as the stratospheric winter winds are clearly very strongly to the east.

Azimuthal errors for the 1.2 KT surface explosion were reported as: 0.8°S, 1.8°, 0.0°, 6.0°S, aand 5.9°S for stations, Pyote, Ft. Lewis, Eagle Mt. Lake, Breckinridge and Eglin AFB, respectively. For the underground explosion, azimuthal errors were reported to be: 0.2°N, 5.7°E, 0.0°, 0.1°N, 4.9°S, 3.5°N and 5.8°N for the Pyote, Ft. Lewis, Eagle Mt. Lake, Breckinridge, Eglin AFB, Washington, DC, and Belmar stations, respectively.

For possible interest to those involved in designing and positioning infrasonic arrays, Table 4 provides a summary of the station noise levels reported during the conduct of the BUSTER and JANGLE test series, and Figures 7, 8 and 9 provide, respectively, graphical waveforms for the 1.2 KT underground explosion recorded at

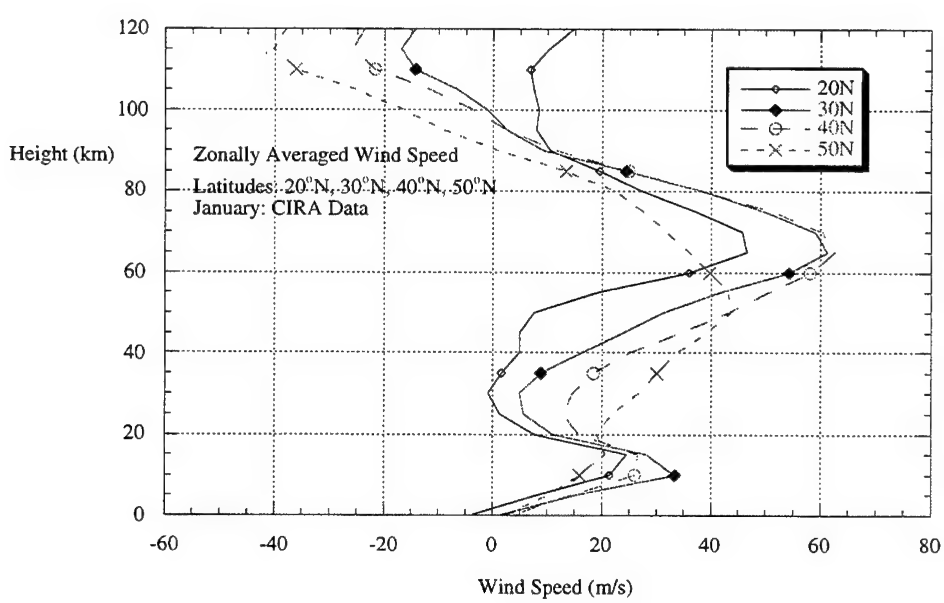


Figure 6. Zonally averaged winds for latitude 40°N for the month of January. Positive values of wind speed indicate that the winds are from the west-to-east. [Figure constructed based on the CIRA-86 data set.]

Table 4. Reported station noise levels during the BUSTER and JANGLE atmospheric test series which was conducted in 1951. The indicated noise levels are peak-to-peak levels in µbar. The dates in the table correspond to test days. The 1.2 KT Sugar test was conducted on 11/19 and the 1.2 KT Uncle test was conducted on 11/29. [Data taken from *Olmsted* (1952a).]

Station	10/28	10/30	11/1	11/5	11/19	11/29
San DIego	2	6	12	5	4	6
Pyote AFB, TX	2.5	3	8	25	4	3
Ft. Lewis, WA	2	2	2	1	2	2
Eagle Mt. Lakee	3	11	3	2	3	5
Breckenridge, KY	3	2	11	3	6	3
Eglin AFB,FL	1	2.4	2	3	3	1
Washington, DC	2.5	1	3	5	13	8
Belmar, NJ	4	5	58	12	49	2
Oahu	12	5	7	12	16	24

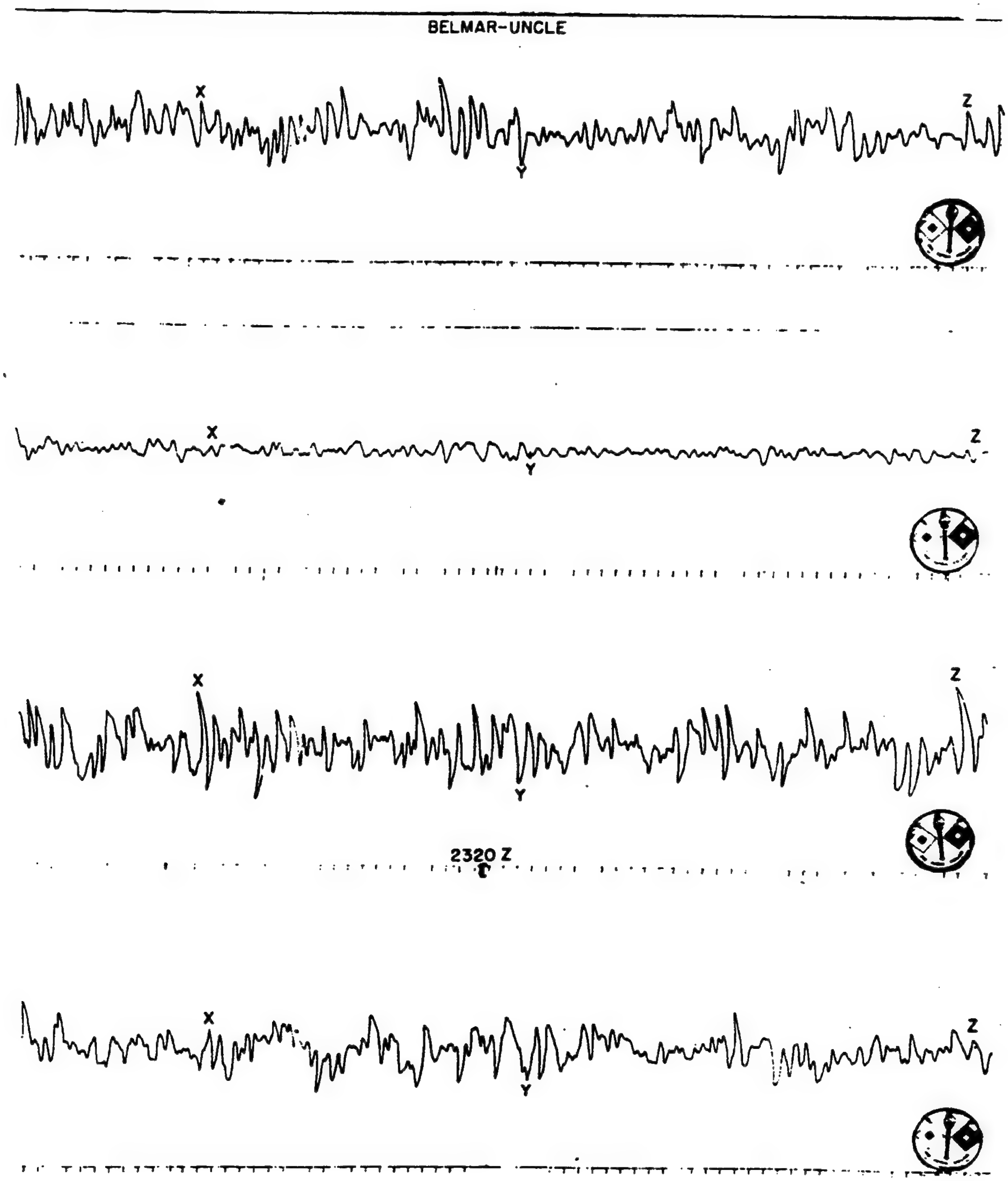


Figure 7. Graphic records for the 1.2 KT underground explosion as recorded at the Belmar, NJ infrasonic array manned by the U.S. Army Signal Corps. The noise background was reported as 2.0 μbar and the maximum signal amplitude as 5.8 μbar. The four traces are evidently from each of the four microphones making up the array and the second channel presumably had background or electronic noise problems. [Figure adopted from *Crenshaw, Lonnie and Pressman* (1952).]

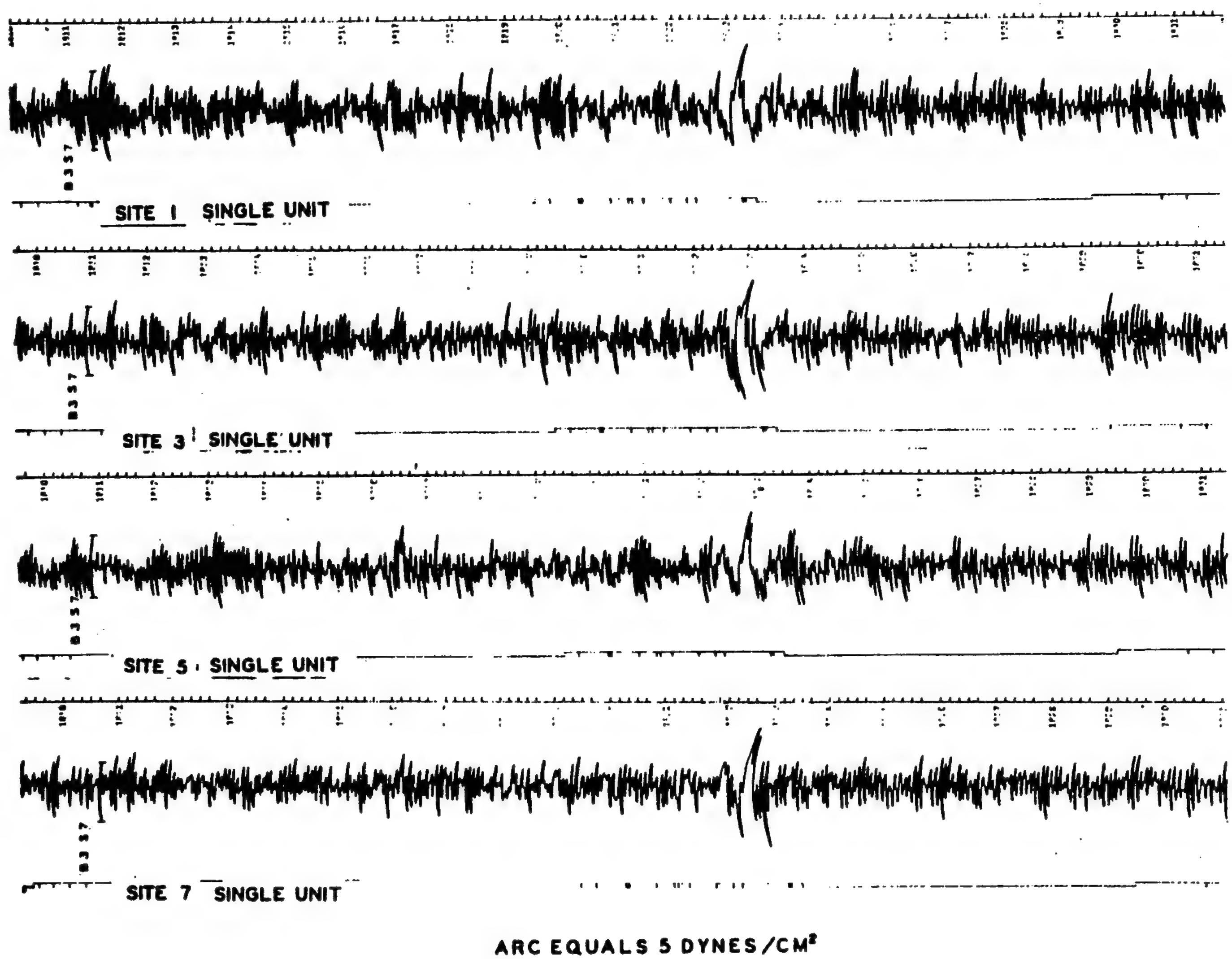


Figure 8. Graphic records for the 1.2 KT surface explosion as recorded at the Fort Lewis-Mchord AFB, WA infrasonic array manned by the NBS. The noise maximum peak-to-peak signal amplitude was observed to be 5 μbar and the signal-to-noise ratio reported to be 2.5. The four traces are from four of the sensors comprising the infrasonic array and are characterized by a pulse-like arrival in a background field made up, in part, of microbaroms. [Figure adopted from *Chrzanowski, et al.*, (1952).]

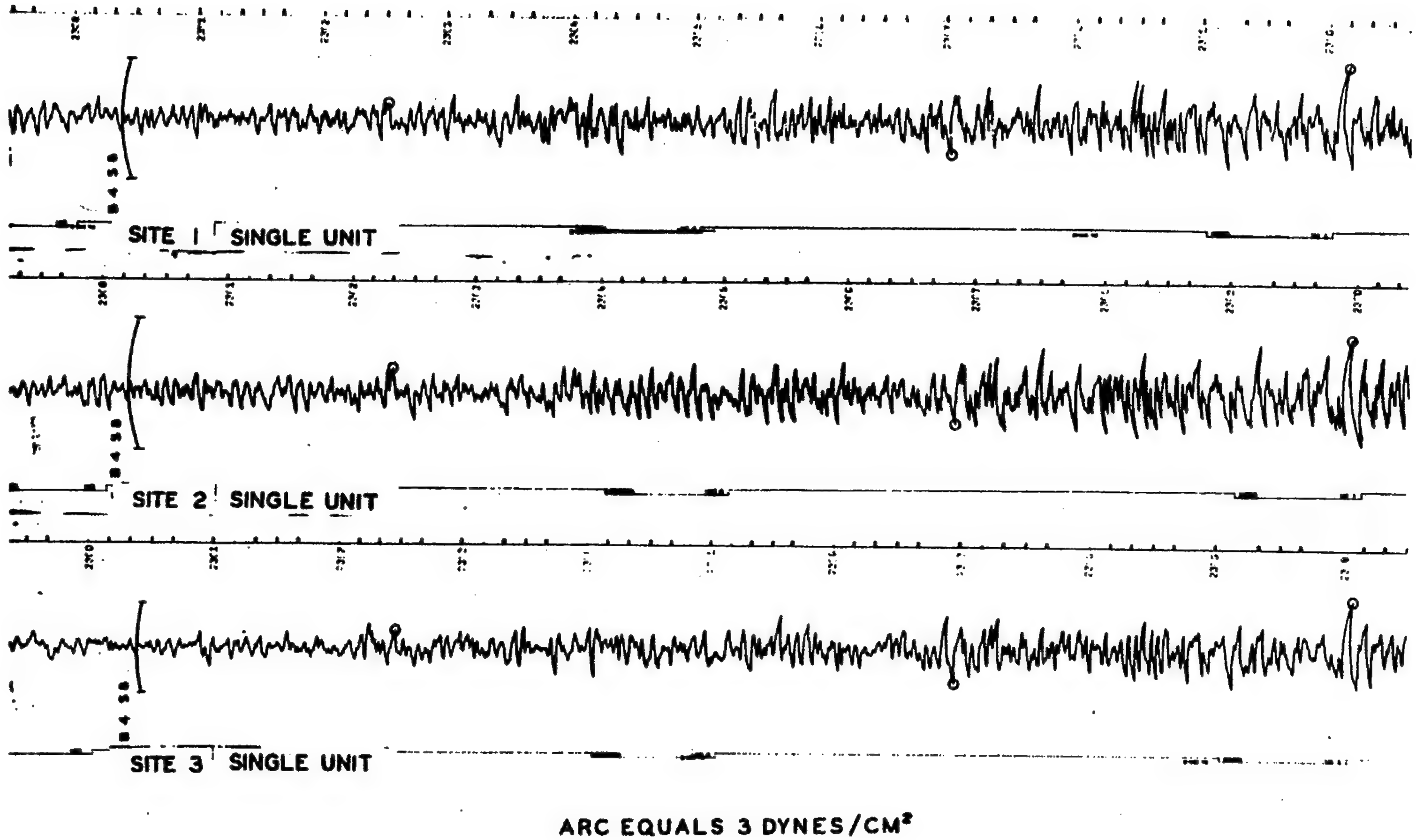


Figure 9. Graphic records for the 1.2 KT underground explosion as recorded at the Washington, DC infrasonic station manned by the NBS. The arcs at the left-hand ends of the traces provide the amplitude scale in μbar peak-to-peak for the particular trace. Symbols such as B458 on each trace near the arcs identify particular amplifier gain settings. The records have been shifted in time so that correlatable points on the traces appear along a vertical line on the figure. The circles locate some, but not all of the correlatable prominences. The record section has significant 2.5 Hz and 4 Hz frequency content. In addition, analysis shows that there is considerable energy in the 10 s to 20 s period region. [Figure and material for the caption adopted from *Chrzanowski, et al.*, (1952)]

Belmar, NJ, the 1.2 KT surface explosion recorded at Ft Lewis and the 1.2 KT underground explosion recorded at Washington, DC.

The TUMBLER-SNAPPER test series took place during the time period extending from April 1, 1952 through June 5, 1952 and involved the detonation of two air dropped 1 KT devices: Able and Baker. There were eight recording stations for this test series: Ft. Lewis, Pyote AFB, Breckinridge, KY, Washington, DC, Belmar, Fairbanks and Oahu. None of the stations detected the Able explosion as they were not operational at the time. Of the eight stations operational for the Baker test, only two detected the explosion: Ft. Lewis, WA, (1230 km) and Pyote AFB, TX, (1350 km) with azimuthal errors: 0.6^{o} and 2.3^{o}N, respectively. The upper panel of Table 5 summarizes the performance and signal characteristics determined for the two detecting stations and for the much lower yield explosions detonated in the UPSHOT KNOTHOLE test series (see below).

Inspection of Table 5 indicates that the maximum detection range was 1350 km (Pyote AFB, TX) which is considerably shorter than the 2818 km detection range for the 1.2 KT surface explosion detonated in the BUSTER and JANGLE test series and for the 3585 km detection of the 1.2 KT underground explosion at Belmar, New Jersey, during the same test series. Table 6 provides noise data reported by *Olmsted* (1952b). A comparison of the station noise data in this table and with that shown in Table 4 for the BUSTER and JANGLE test series indicates that the noise levels were generally higher during the low yield explosions in TUMBLER-SNAPPER than in BUSTER and JANGLE, although the noise level at Fairbanks appears to be quite low; i.e., 0.7 μbar. The reason why the stations east of the NTS failed to detect the Baker shot may be due to the fact that the stratospheric winds were not as strongly westwardly as shown in Figure 10 which plots zonally averaged winds for the latitudes 20^{o}N, 30^{o}N, 40^{o}N and 50^{o}N.

Table 5. Stations recording the 1.2 kt shots Ruby and Uncle in the JANGLE test series together with selected properties of the received waveforms. In the table P-P denotes peak-to-peak. [Data taken from *Olmsted* (1952b) and *Olmsted* (1954).]

Station	Travel Speed (m/s)	Duration (min)	Max. P-P Signal Amplitude (μbar)	Avg. P-P Noise (μbar)	Signal Periods (s)	Measured Azimuth	Apparent Velocity (m/s)	Range (km)
Shot Baker in the TUMBLER-SNAPPER Test Series: Yield 1.0 KT								
Ft. Lewis WA		16	13.4	2.6	4-20	152.6°	304-360	1230
Pyote AFB, FL		6	22.4	13.0	4-8	303.0°	315-344	1350
Shot Ruth in the UPSHOT KNOTHOLE Test Series: Yield 0.2 KT								
Los Angeles, CA			18.0	< 1.0	6,14			380
San Diego, CA		10	10.0	< 1.0	3-5,12		320-380	475
Dateland, CA		10	80.0	< 1.0	2,13		350-435	505
Gila Bend, AZ		10	80.0	< 1.0	1,2,12			530
Pyote AFB, TX		3	6.8	2.0	2-4		346-358	1350
Shot Ray in the UPSHOT KNOTHOLE Test Series: Yield 0.2 KT								
Los Angeles, CA		2.5	16	< 1.0	2,6,16			380
San Diego, CA		4.0	16	< 10	2,5			475
Dateland		6.0	16	0	1,3		350-365	505
Gila Bend		6.0	80	0	2			530

Table 6. Reported station noise levels during the TUMBLER-SNAPPER atmospheric test series which was conducted in 1952. The indicated noise levels are 0-to-peak levels in μbar. The 1.0 KT Baker test took place on April 15, 1952. [Data taken from *Olmsted* (1952b).]

Station	4/15	4/22	5/1	5/7	5/15	6/1	6/5
Ft. Lewis, WA	1.3	3.0	2.0	0.7	1.1	0.6	0.8
Pyote AFB, TX	6.5	1.9	1.5	0.5	1.2	1.2	0.4
Breckinridge, KY	7.3	5.0	1.0	1.8	4.7	9.2	2.0
Washington, DC	6.6	0.5	2.2	6.3	1.4	2.2	3.2
Belmar, NJ	6.2	7.3	23.6	31.4	25.7	2.5	1.9
Fairbanks, AL	0.7	0.5	0.5	1.2	0.4	0.5	0.3
Oahu, HI	5.2	11.9	7.6	4.3	1.7	0.9	3.0

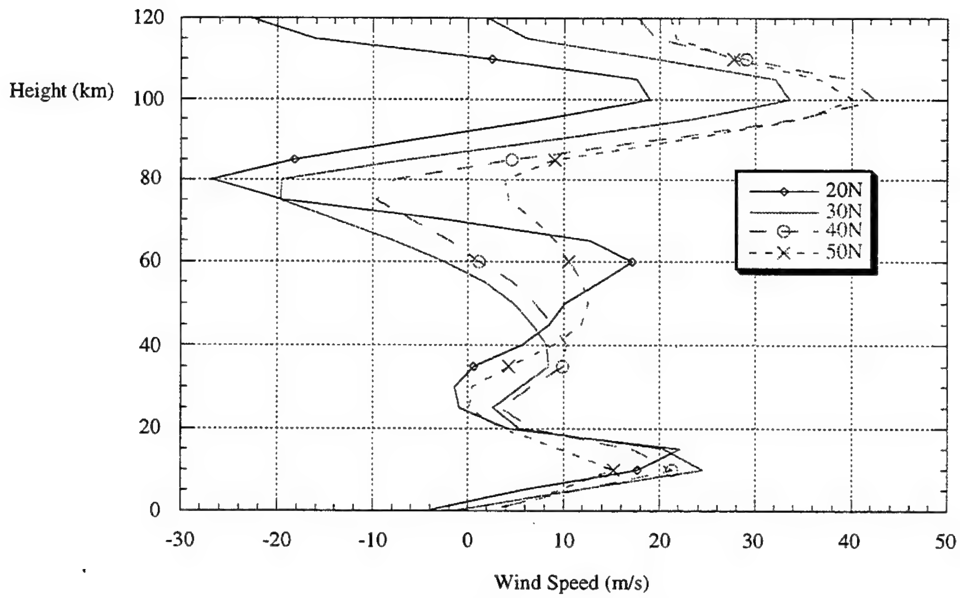


Figure 10. Zonally averaged winds for latitudes 20^{o}N, 30^{o}N, 40^{o}N and 50^{o}N for the month of April. [Figure constructed based on the CIRA-86 data set.]

The OPERATION IVY atmospheric test series was conducted during the fall of 1952 at the Enewetak test site in the south Pacific. The series consisted of only two explosions: a 10.4 MT surface explosion and a 500 KT air dropped explosion and, accordingly, the results of the tests are not particularly relevant for the low yield explosions of interest herein.

The OPERATION UPSHOT-KNOTHOLE test series was conducted during the time period extending from March 17, 1953 to June 4, 1953 and involved the detonation of two air dropped explosions of very low yield: 0.2 KT. Fifteen stations were operative for the test series: some at very long ranges from the NTS because, presumably, the explosive yields planned for the test series were as high as 61 KT. Typical stations operative for the test series have been indicated in Table 2.

For the very small yield tests, only a very few stations were able to detect the events as indicated in the lower two panels of Table 5. For the first 0.2 KT explosion, detonated

on March 31, 1953, the maximum detection range was 1350 km and for the second explosion, detonated on April 11, 1953, the maximum detection range was only 530 km. In an attempt to understand a difference of 2.6 in detection range, Table 7 provides measured noise levels recorded at the various stations during the conduct of the test series and it is evident that the noise level at the 1350 km station (Pyote AFB, TX) was over three times higher on April 11, 1953 than on March 31, 1953. Inspection of Table 5 shows that the maximum peak-to-peak signal level at the Pyote AFB on March 31, 1953 was relatively small, i.e., 6 μbar.

The work summarized above generally support the views of some in the infrasonic monitoring community that 4-element station spacing should not exceed 2,500 km to assure a global network detection capability at a 1 KT threshold [see, for example, *Christie* (1995).] The results also emphasize the importance of selecting infrasonic sites with naturally occurring low noise levels.

2.2. Monitoring at Short Ranges

The monitoring program conducted by the Sandia National Laboratory is described in two reports authored by *Reed* (1969 & 1974). The Sandia effort was initiated in 1951 following the Operation RANGER test series which was conducted during January and February of 1951. According to the *DOE* (1994), this test series involved five air-dropped nuclear explosions: two having yields of 1 KT (1/28/51 and 2/1/51); two having yields of 8 KT (1/28/51 and 2/2/51); and one having a yield of 22 KT (2/6/51). Evidently, one or more of these tests produced strong acoustic effects (broken windows, etc.) in the communities surrounding the NTS and, accordingly, in 1951 a Blast Prediction Unit was established.

The Blast Prediction Unit was assigned three primary responsibilities: to determine the causes of the high acoustic levels out to ranges of approximately 250 km; to develop methods of predicting the levels to be anticipated in the communities surrounding the NTS from atmospheric tests of varying yields and configuration; and to make infrasound recordings for research and for verification purposes. During the time period extending

Table 7. Reported station noise levels during the UPSHOT-KNOTHOLE atmospheric test series which was conducted in 1953. The indicated noise levels are 0-to-peak levels in μbars. N.O. denotes not operational. The two 0.2 KT tests were conducted on April 31, 1953 and April 11, 1953. [Data taken from *Olmsted and Nowak* (1954).]

Station	3/17	3/24	3/31	4/6	4/18	4/11	4/25/	5/19	5/8	5/25	6/4
Los Angeles, CA	<5	<2.5	<0.5	<0.5	<1.5	<0.5	<0.5	15	20	<3	<1
San Diego, CA	<2.5	<2.5	<0.5	<2.5	<1.5	<5	<0.5	≤2.5	23	<2.5	<1
Dateland, AZ	0	0	<0.5	<2.5	<5	0	<0.5	<0.7	8.5		<1
Gila Bend, AZ	<2.5	0	<0.5	<2.5	N.O.	0	N.O.	N.O.	N.O.		
Ft. Lewis, WA	1.5	1.0	1.3	0.5	0.3	2.2	0.6	0.4	8	1.5	1.3
Pyote AFB, TX	1.3	1.7	1.0	1.5	3.2	0.4	4.7	2.2	1.9	1.4	
Barksdale AFB, LA	1.8	2.3	12	2.2	12	1.7	1.2	1.8	1.3		1.5
Washington, DC	4.1	4.6	7.2	3.0-13.4	2.4	4.6	5.5	0.6	2.2	0.6	1.0
Belmar, NJ	5.6		12.5	9.5	2.5	17.5	2.5	0.9	4.2		
Fairbanks, AL	0.3	0.3	0.3	1.6	1.4	0.2	1.2	0.5	3.3		3.8
Oahu	7.0	3.3	2.5	1.4	3.7	1.2	1.4	3.8	1.7	2.9	3.0

from 1953 to 1962 there were approximately "15,000 wave passages" recorded by the program at station ranges extending from about 7 km to 270 km. The microbarograph records were recorded on paper at a speed of 25-mm/s so that up to 15 m of paper was produced in monitoring several of the tests. All of the data acquired during the program have been archived at Sandia and are available as unclassified records [*Reed* (1974) and *Bedeaux* (1996)].

The microbarograph sensors used in the program consisted of a "Bourdon tube aneroid barometer cell originally built by the Wiancko Co. This actuated an electric pickup that modulated an FM carrier signal which was hard wired to signal amplifiers. Various set ranges could be switched to allow approximately full-scale recording on the most sensitive channel, called the A-pen, based on predicted wave amplitude" [*Reed* (1974)]. The "high frequency response for this system was generally limited by the recorder to lower than about 30 Hz. Low-frequency response was adjusted by a bleed plug in the back chamber surrounding the Bourdon tube. Usually, a flat response to 0.05 Hz was desired. On occasions of very large explosions (multimegatons) with long compression durations, this bleed plug was set for 50 seconds of bleed time, but this was not very easily or accurately obtained" [*Reed*, 1974].

A listing of stations which were involved in monitoring explosions having a yield of 4 KT or less is provided in Table 8 and a geographical map of station locations is provided in Figure 11. As indicated, there were primary and secondary stations involved and, as shown later, the number of stations varied from test event to test event and station ranges varied at a particular site. In the table, the indicated station bearing and range coordinates are referenced to Area 7 of Yucca Flat. For the most part, station ranges are 272 km or less with the exceptions being the Albuquerque, NM and Pasadena, CA stations.

For the indicated station ranges, *Reed* (1974) notes that there can be several "acoustic wave packets that arrive over a 10-minute time span." The various arrival packets

Table 8. Station locations used to study the climatology of airblast propagations from NTS atmospheric nuclear explosions. The distances and bearings are referenced to Area 7, Yucca Flat, and C for a particular location indicates "close" and F indicates "far". [Data adopted from *Reed* (1969).]

Primary Stations

Station	Bearing (Deg)	Range (km)
Bishop, CA	278	210.9
Boulder City, NV	139	163.4
Caliente, NV	64	155.4
China Lake, CA	223	213.4
Indian Springs, NV	142	63.1
Las Vegas, NV	142	129.2
Lund, NV	25	218.5
St. George, UT	90	217.6
Tonopah, NV	317	146.0

Secondary Stations

Station	Bearing (Deg)	Range (km)
Albuquerque, NM	110	890.0
Beatty, NV	257	67.1
BJY, NV	205	6.8
Cedar City C	076	269.4
Cedar City F	076	271.0
Cedar City, UT	075	272.3
Coaldale, NV	302	188.5
Coyote, NV	050	65.2
CP-1	191	16.7
CP-1-P	179	14.3
CP-M1	185	17.0
FFT	179	31.0
FFT-P	170	27.2
FFO	178	43.6
Glendale, UT	110	139.9
Goldfield, NV	304	129.2
Goldfield C	304	127.1

Table .8 (Cont.). Station locations used to study the climatology of airblast propagations from NTS atmospheric nuclear explosions. The distances and bearings are referenced to Area 7, Yucca Flat, and C for a particular location indicates "close" and F indicates "far". [Data adopted from *Reed* (1969).]

Station	Bearing (Deg)	Range (km)
Henderson, NV	39	141.4
Indian Springs C	154	62.5
Indian Springs F	149	68.5
Las Vegas C	137	101.2
Las Vegas F,	137	102.4
Mercury, NV	177	47.2
MER-P	172	42.7
MOB	189	17.0
OBA	183	19.4
Pasadena, CA	212	374.6
SCU	178	40.53
St. George C	082	210.9
St. George F	082	212.1
UCC	180	19.5
XFM	185	21.2
XMF-1	185	21.0
XMF-2	185	21.0

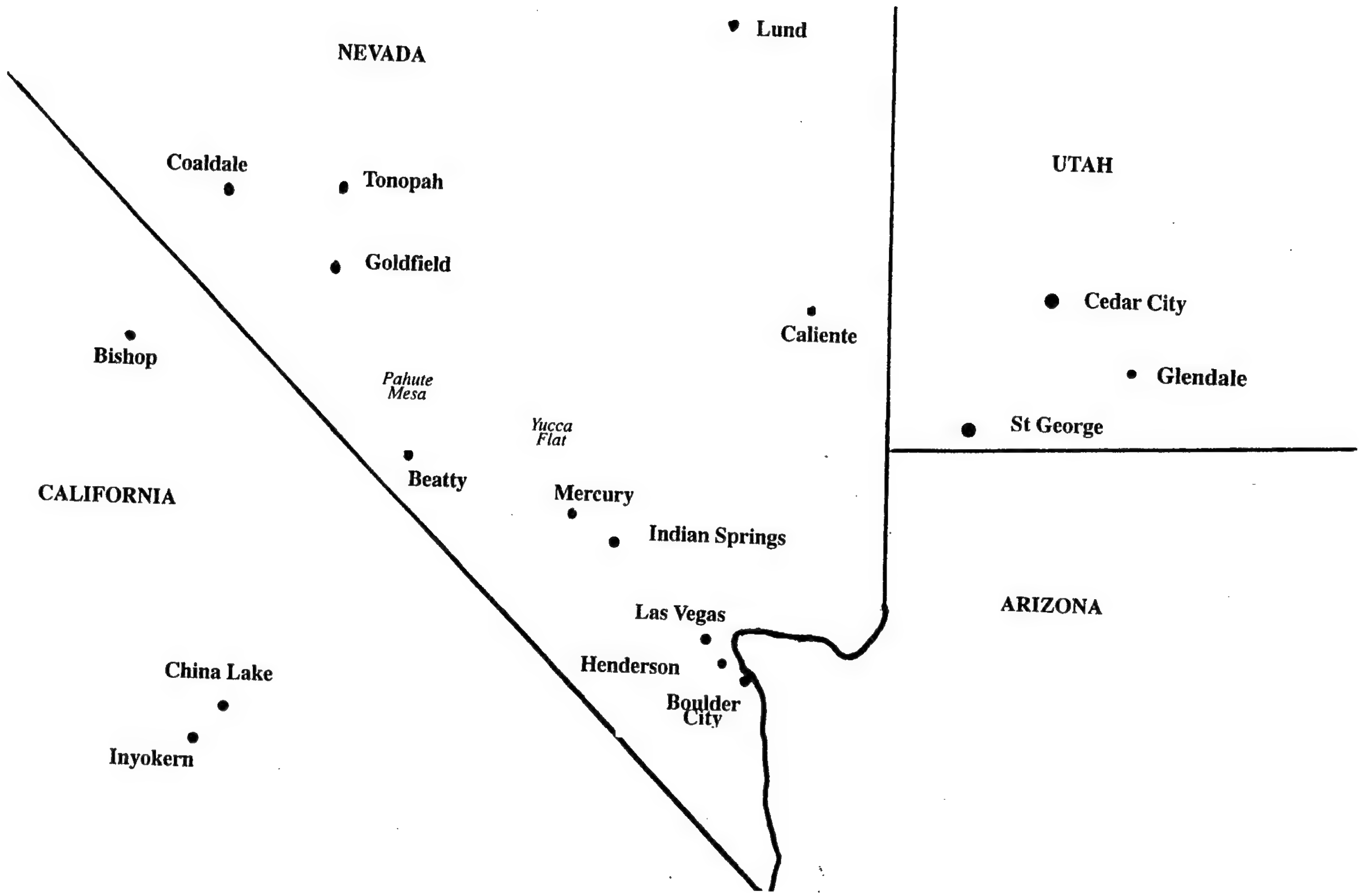


Figure 11. The locations of some of the stations used in the short range monitoring program of NTS atmospheric nuclear explosions conducted by the Sandia National Laboratory [*Reed* (1969)]. As indicated in the text, only a select number of the indicated stations were operative for a particular test series.

are conveniently referred to as tropospihereic, ozonospheric and ionospheric arrivals and exist at a given time because of a station's particular range from NTS and the existing propagation conditions at the time of an explosive event. Indeed, several propagation paths are identified in addition to scattered or diffracted waves:

• near ground propagation downwind or beneath a temperature inversion (a tropospheric path)

• sound-duct propagation caused by jet stream winds at altitudes extending from 6 km to 10 km (a tropospheric path)

• downwind ducted propagation caused by the presence of the warm layer in the ozonosphere at an approximate altitude of 50 km (an ozonospheric path)

• seasonally dependent propagation guided by the ionospheric duct at an approximate altitude of 100 km (an ionospheric path).

In exhibiting seasonal patterns for infrasonic propagation to the various microbarograph stations, *Reed* (1969) normalized the yield data to correspond to a "reference yield" of 1.0 KT for a free air blast. To do so, it was necessary to remove the height-of-burst (h_{ob}) or "Mach stem" effects which results in higher apparent yields owing to the constructive interference between the ground reflected and the direct or outgoing shock waves.

The procedure utilized by *Reed* (1969) involved the introduction of a scaled h_{ob} defined according to the relation

$$h^s_{ob} = \frac{h^a_{ob}}{W^{1/3}}$$

where the superscript "s" referes to the scaled value, the superscript "a" refers to the actual height of burst and W is the explosive yield in KT. Next a quantity referred to as the apparent yield, W_a, was introduced by fitting the ratio (W_a/W) to the scaled height of burst computed from unspecified 2 lb/in^2 over-pressure contours evidently established from measured data on nuclear explosions of various yields. The curve utilized by *Reed* (1969) is shown in Figure 12 which illustrates that the optimum detonation height for a 1 KT

device is approximately 900 ft. The smooth curve in the figure is a 9-th order polynomial fit to the data.

Assuming that the overpressure amplitude decayed with range according to the relation

$$A \approx \frac{K}{R^{1.2}}$$

where K is a constant, *Reed* (1969) noted that, at a fixed range, the amplitude of the received waveform, Amp, scales with W_a according to the relaton

$$\mathrm{Amp} \approx K_1 W_a$$

where K_1 is a constant. As noted by *Reed* (1969) the $1/(R)^{1.2}$ range fall-off, rather than the more normal acoustic 1/R fall-off, reflects the incorporation of those experiments lacking a direct or refracted arrival or in which significant energy is coupled to the ground.

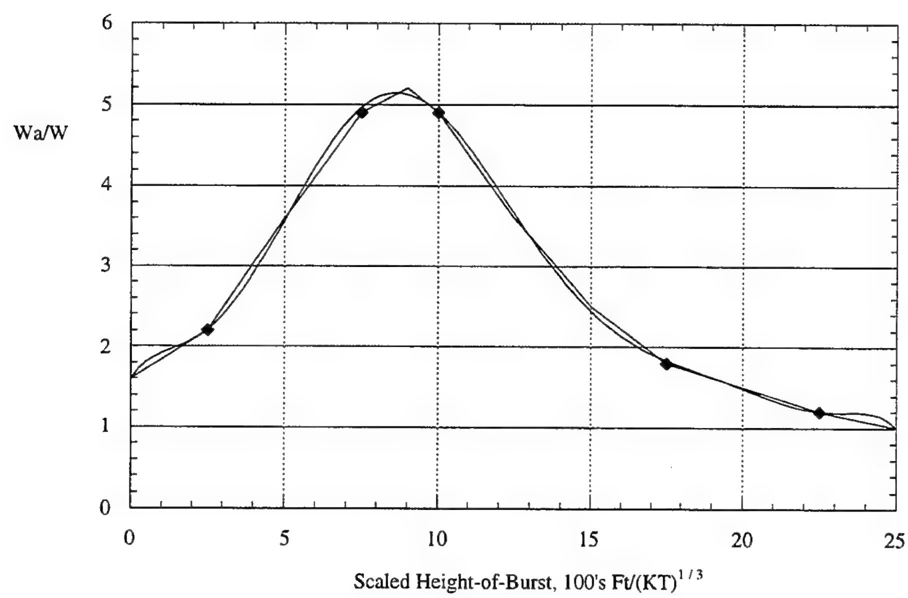


Figure 12. The ratio of the equivalent yield, free air burst, W_a to the chemical yield, W, as a function of the scaled height-of-burst. [Figure based on data provided by *Reed* (1969).]

Although waveform data have not been published relevant to low-yield events monitored by the Sandia National Laboratory, *Reed* (1969), in his investigation of the climatology of airblast propagation from the NTS, has published recorded peak-to-peak

signal amplitudes for all of the explosions conducted during the BUSTER and JANGLE, TUMBLER-SNAPPER, UPSHOT-KNOTHOLE, TEAPOT, PLUMBBOB and HARDTACK II test series and, in this connection, Table 9 provides a listing of the explosions having a yield less than 4 KT for which actual recorded amplitude data is available at a select number of station sites.

Table 10 presents peak-to-peak signal amplitude data as recorded at eight microbarograph stations for the low-yield explosions of the BUSTER & JANGLE test series. As indicated, both tropospheric and ionospheric arrivals were recorded at several of the staions with the ozonospheric arrivals generally higher than the tropospheric arrivals. As mentioned previously, the station ranges were not held constant throughout a given test series and Table 11 provides a listing of station ranges for each of the four low yield explosions of the BUSTER & JANGLE test series.

Tables 12 and 13 provide, respectively, similar data for the low-yield explosions conducted during the TUMBLER-SNAPPER and UPSHOT-KNOTHOLE test series.

In a similar fashion Tables 14 and 15 provide, respectively, peak-to-peak amplitude data and station ranges for the low-yield tests conducted during Operation TEAPOT. Inspection of Table 14 shows that two of the stations (Bishop, CA and Inyokern, NV) recorded both ozonospheric and ionospheric arrivals.

Tables 16 and 17 provide, respectively, peak-to-peak amplitude data and associated station ranges for the PLUMBBOB test series and Tables 18 and 19 provide similar data for the Operation HARDTACK-II test series.

Table 9. Low yield explosions conducted at the NTS and for which peak-to-peak amplitude data for various propagation paths are available. In the table, B&J refers to the BUSTER & JANGLE test series, T-S to the TUMBLER-SNAPPER test series, TEPT to the TEAPOT test series, PLMB to the PLUMBBOB test series and HARDTACK-II to the HARDTACK-II test series. The location designators refer to specific site locations at the NTS. [Data adopted from *Reed* (1969).]

Event	Series	Date	Time	Yield(KT)	Burst Height (FT)	Location	Wa	(Wa)0.4
Able	B & J	10/22/51	1400	<0.1	100	A-3	≥0.238	>0.562
Baker	B & J	10/28/51	1520	3.5	1118	A-3	16.9	3.09
Sugar	B & J	11/19/51	1700	1.2	4	A-10	1.92	1.30
Uncle	B & J	11/29/51	2000	1.2	17	A-10	1.92(est.)	1.30 (est.)
Able	T-S	4/1/52	1700	1.2	793	FF	5.45	1.97
Baker	T-S	4/15/52	1730	1.2	1109	A-3	5.55	1.99
Ruth	U-K	3/31/53	1300	0.2	1300	A-7,5	0.83	0.73
Ray	U-K	4/11/53	1245	0.2	1245	T 4A	0.42	0.71
Wasp	TEPT	2/3/55	2000	1.2	762	T-7-4	5.72	2.01
Moth	TEPT	2/22/55	1345	2.4	300	T-3	5.45	1.97
Hornet	TEPT	3/12/55	1320	3.6	300	T-3A	7.85	2.28
ESS	TEPT	3/23/55	2030	1.1	-67	T-10		
Wasp-Prime	TEPT	3/29/55	1800	3.2	740	T-7-4	11.6	2.67
HA	TEPT	4/6/55	1800	3.3	36,620	T-5G	3.3	1.6
Post	TEPT	4/9/55	1230	1.5	300	T-9C	3.6	1.7
Franklin	PLMB	6/2/57	1155	0.14	300	T-3	0.569	0.80
Lassen	PLMB	6/5/57	1145	0.47	500	B-9A	4.7×10^{-4}	4.97×10^{-2}
John	PLMB	7/19/57	1400	2.0	30,000	A-9	2	1.32
Wheeler	PLMB	9/6/57	1245	0.2	500	B-9A	1.025	1.01
LaPlace	PLMB	9/8/57	1300	1.0	750	B-7B		
Ranier	PLMB	9/19/57	1700	1.7	-790	U-126		

Table 9 (Cont.). Low yield explosions conducted at the NTS and for which peak-to-peak amplitude data for various propagation paths are available. In the table, B&J refers to the BUSTER & JANGLE test series, T-S to the TUMBLER-SNAPPER test series, TEPT to the TEAPOT test series, PLMB to the PLUMBBOB test series and HARDTACK-II to the HARDTACK-II test series. The location designators refer to specific locations at the NTS. [Data adopted from *Reed* (1969).]

Event	Series	Date	Time	Yield(KT)	Burst Height (FT)	Location	Wa	$(Wa)^{0.4}$
Eddy	HRDT-II	9/19/58	1400	0.083	500	B-7B	0.34	0.65
Mora	HRDT-II	9/29/58	1405	2.0	1500	B-7B	7.76	2.27
Hidalgo	HRDT-II	10/5/58	1410	0.077	377	B-7B	0.393	0.689
Quay	HRDT-II	10/10/58	1430	0.079	100	T-7C	0.182	0.506
Lea	HRDT-II	10/13/58	1320	1.4	1500	B-7B	4.37	1.80
Hamilton	HRDT-II	10/15/58	1600	1.17	50	FF-T-1	4×10^{-3}	0.111
Dona Ana	HRDT-II	10/16/58	1420	0.037	500	B-7B	0.0904	0.373
Rio Arriba	HRDT-II	10/18/58	1425	0.090	70	T-3S	0.187	0.512
Vesta	HRDT-II	10/18/58	2300	0.024	0	GG-9	0.0456	0.290
Wrangell	HRDT-II	10/22/58	1650	0.115	1500	B-FF	0.115	0.421
Rushmore	HRDT-II	10/22/58	2340	0.133	500	B-9B	0.960	0.984
Catron	HRDT-II	10/24/58	1500	0.021	72.5	T-3	0.0498	0.299
DeBaca	HRDT-II	10/26/58	1600	2.2	1500	B-7B	8.93	2.41
Chavez	HRDT-II	10/27/58	1430	0.6	1430	A-3		

Table 10. Signal amplitudes recorded from low yield explosions detonated in the BUSTER & JANGLE test series. In the table, T refers to a tropospheric arrival and O to an ozonospheric arrival. The numbers in parentheses denote the peak-to-peak amplitude of the recorded pressure waves in *m*bar. [Data adopted from *Reed* (1969)].

Station	Able (≤0.1KT)		Baker (3.5 KT)		Sugar(1.2 KT)		Uncle (1.2KT)	
Las Vegas	T(86)		T(9.5)	O(134)		O(25)	T(29.5)	O(15.4)
Henderson	T(47)	O(10.7)	T(5.5)	O(>180)		O(93)	T(40)	O(130)
Boulder City	T(51)	O(12.8)		O(415)		O(110)	T(4.2)	O(102)
Caliente			T(15.5)	O(85)	T(625)		T(142)	O(71)
St George		O(38.5)		O(345)	T(163)	O(152)	T(102)	O(610)
Indian Springs	T(520)		T(53)				T(130)	
Beatty	T(65)		T(>82)				T(25.5)	
Goldfield	T(930)							O(33)

Table 11. Stations and ranges in km from the NTS for the BUSTER & JANGLE test series conducted in 1951. The yields of the explosions are indicated in the parentheses. [Data adopted from *Reed* (1969).]

Stations	Able(<0.1KT)	Baker(3.5 KT)	Sugar(1.2 KT)	Uncle(1.2 KT)
Las Vegas	123.4	123.4	132.0	133.5
Henderson	141.4	141.1	151.2	151.2
Boulder City	159.4	159.4	169.2	169.2
Caliente	146.6	146.6	143.9	143.9
St. George	217.3	217.3	217.3	217.8
Indian Springs		60.0	70.7	70.7
Beatty		67.1	68.6	68.6
Goldfield		129.2	121.6	121.6

Table 12. Signal amplitudes recorded from low yield explosions detonated in the TUMBLER-SNAPPER and UPSHOT-KNOTHOLE test series. In the table, T refers to a tropospheric arrival, O to an ozonospheric arrival and I to the ionospheric arrival. The numbers in parentheses denote the peak-to-peak amplitudes of the recorded pressure waves in *m*bar. [Data adopted from *Reed* (1969)].

Station	Able(1.1 KT)	Baker(1.1 KT)	Ruth(0.2KT)	Ray(0.2KT)
Las Vegas		T(31) O(47)		
Las Vegas C	T(280)		T(132)	T(420)
Las Vegas F	T(300)		T(110)	T(476)
Henderson	T(40) O(130)	T(65)		T(620)
Boulder City	O(105)		T(22.6)	T(200)
Boulder City C		T(520) O(180)		
Boulder City F		T(600) O(220)		
Caliente	O(21)	T(480)	T(123)	
Goldfield	T(472)			
Goldfield C			O(10.2)	
St George				
St George C	T(50) O(98)	O(250)	T(20) O(220)	O(260)
St George F	T(210) O(440)	O(420)	O(260)	
Indian Springs C			T(690)	T(2663)
Indian Springs F				T(2250)
CP-1			T(8400)	T(5300)

Table 12 (Cont.). Signal amplitudes recorded from low yield explosions detonated in the TUMBLER-SNAPPER and UPSHOT-KNOTHOLE test series. In the table, T refers to a tropospheric arrival and O to an ozonospheric arrival. The numbers in parentheses denote the peak-to-peak amplitudes of the recorded pressure waves in *m*bar. [Data adopted from *Reed* (1969)].

Station	Able(1.1 KT)	Baker(1.1 KT)	Ruth(0.2KT)	Ray(0.2KT)
XFM				T(4800)
XMF-1				
XMF-2			T(4500)	
FFT			T(3200)	
SCU			T(3900)	T(3300)
Mercury			T(2160)	T(2080)
Cedar City C			T(7.8)	
Cedar City F				T(84)
Albuquerque			O(29.3)	
Pasadena			O(22.0) I(20.0)	

Table 13. Stations and ranges in km from the NTS for the TUMBLER-SNAPPER and UPSHOT-KNOTHOLE test series conducted during 1952 to 1953. [Data adopted from *Reed* (1969).]

Stations	Able(1.1 KT)	Baker(1.2 KT)	Ruth(0.2 KT)	Ray(0.2 KT)
Albuquerque		890.0	890.0	
Boulder City	135.6	159.4	162.1	170.1
Caliente	154.5		145.5	
Cedar City C			269.4	
Cedar City F			271.0	
CP-1			16.7	17.0
FFT			31.0	
Goldfield	143.9			
Goldfield C			127.1	
Henderson	121.6	141.4		159.7
Indian Springs C			62.5	67.1
Indian Springs F				68.5
Las Vegas		123.1		
Las Vegas C	101.2		130.8	136.2
Las Vegas F	102.4		132.6	137.8
Mercury			47.2	49.3
Pasadena			374.6	

Table 13 (Cont.). Stations and ranges in km from the NTS for the TUMBLER-SNAPPER and UPSHOT-KNOTHOLE test series conducted during 1952 to 1953. [Data adopted from *Reed* (1969).]

Stations	Able(1.1 KT)	Baker(1.2 KT)	Ruth(0.2 KT)	Ray(0.2 KT)
SCU			40.5	43.3
St. George C	210.9	217.0	216.0	
St. George F	212.1	218.2	217.0	
XFM				23.6
XMF-1			21.0	
XMF-2			21.0	

Table 14. Signal amplitudes recorded from selected low yield explosions detonated in the TEAPOT test series. In the table, T refers to a tropospheric arrival, O to an ozonospheric arrival and I to the ionospheric arrival. The numbers in parentheses denote the peak-to-peak amplitudes of the recorded pressure waves in *m*bar. [Data adopted from *Reed* (1969)].

Station	Wasp(1.2 KT)	Moth (2.4 KT)	Hornet(3.6 KT)	ESS(1.1KT)
CP-1	T(5040)	T(14640)	T(13080)	T(400)
FFT				T(384)
Mercury	T(2070)	T(5800)	T(1560)	T(230)
Indian Springs	T(2663)	T(5544)	T(728)	T(16)
Las Vegas	T(670) O(360)	T(2992) O(88)	T(42) O(148.8)	
Boulder City	T(530) O(140)	T(1121) O(162)	T(12) O(184.2)	O(63)
Caliente	O(1600)	T(32) O(1088)		O(260)
Glendale			T(94.8) O(202.8)	
St. George	T(40) O(260)	T(232) O(1032)	T(20) O(256)	O(166)
Cedar City	O(280)	T(72.6) O(386)		
Lund	O(192)	T(3.6) O(389)	O(410)	O(358)
Tonopah		O(62.4)	O(256.8)	
Bishop		O(4.2) I(>96)	O(120) I(60)	O(12) I(6)
Inyokern		T(4.1) O(4.1) I(52.3)	O(126.3) I(33)	O(7.6) I(13)

Table 14 (Cont.). Signal amplitudes recorded from selected low yield explosions detonated in the TEAPOT test series. In the table, T refers to a tropospheric arrival, O to an ozonospheric arrival and I to the ionospheric arrival. In addition, CP-1-P (1), FFT-P (1) and MER-P (1) indicates that the microbarograh was deployed on a 40 ft pole and (2) indicates that there was no step recorded to show the reflected wave. The numbers in parentheses denote the peak-to-peak amplitudes of the recorded pressure waves in *m*bar. [Data adopted from *Reed* (1969)].

Station	Wasp-Prime(3.2 KT)	HA(3.3 KT)	Post(1.5 KT)
CP-1	T(4068)	T(13200)	T(4680)
FFT-P(1)		T(7760) (2)	
MER-P (1)		T(2208) (2)	
OBA			T(63.7)
Mercury	T(204) O(42)		T(340)
Indian Springs	T(408) O(187)	T(1002)	T(130)
Las Vegas	T(>320) O(248)	T(42) O(138)	T(87)
Boulder City	T(696) O(583)	O(572)	O(342)
Caliente	T(2320) O(496) I(160)	O(474)	O(207)
St. George	T(308) O(368)	O(756)	O(1014)
Tonopah	O(35)	O(65.4)	T(3.6) O(58.2)
Lund		O(204)	O(626)
Bishop	T(277) O(14.4) I(24)	I(54)	O(19.2) I(10.2)
Inyokern	O(91.8)	O(20) I(78)	O(51.0)

Table 15. Stations and ranges in km from the NTS for the TEAPOT test series conducted during 1952 to 1953. [Data adopted from *Reed* (1969).]

Stations/ Yield	Wasp (1.2)	Moth (2.4)	Hornet (3.6)	ESS (1.1)	Wasp-Prime (3.2)	HA (3.3)	Post (1.5)
Boulder	162.0	159.1	158.7	170.6	162.1	161.9	168.3
Caliente	145.9	147.4	148.2	143.9	145.6	151.3	145.2
Cedar City	271.0	272.3					
CP-1	16.8	12.7	11.9	26.1	16.9		20.8
CP-1-P						14.3	
FFT				40.6			
FFT-P						27.2	
Glendale			139.9				
Indian Springs	62.6	58.9	58.3	71.9	62.5	58.7	66.8
Inyokern	213.5	210.3	210.8	220.1	213.2	207.8	216.7
Las Vegas	128.5	127.6	127.1	139.6	130.8	127.9	134.9
Lund	215.8	219.5	221.9	209.4		224.2	213.9
Mercury	47.3	43.1	42.4	55.0	47.2		51.5
MER-P						42.7	
OBA							19.4
St. George	216.4	216.2	216.6	218.0	216.0	219.5	217.2
Tonopah	144.7	147.4	147.8	135.9	144.3	146.9	140.3

Table 16. Signal amplitudes recorded from selected low yield explosions detonated in the PLUMBBOB test series. In the table, T refers to a tropospheric arrival, O to an ozonospheric arrival and I to the ionospheric arrival. The numbers in parentheses denote the peak-to-peal amplitudes of the recorded pressure waves in *m*bar. The notation (1) denotes no signal-to-noise [Data adopted from *Reed* (1969)].

Station	Franklin(0.14 KT)	Lassen(0.47 KT)	John(2 KT)
CP-1	T(6800)	T(80)	T(2440)
Las Vegas	T(3.0) O(24.6)	O(0.4)	T(3.0) O(73.2)
Boulder City	T(1.2) O(24.6)	O(0.4) (1)	O(66) I(12)
St. George	O(6.6) I(21)	O(0.4) (1)	O(34.2) I(45)
Lund			T(22.8) O(52.8) I(63)
Tonopah	T(6) O(48)	O(0.8)	T(6) O(60.2)
Coaldale			O(284) I(20)
Bishop	O(254.4)	O(14)	O(556)
Inyokern	O(568) I(20)	O(6.0)	O(800) I(40)

Table 16 (Cont.). Signal amplitudes recorded from selected low yield explosions detonated in the PLUMBBOB test series. In the table, T refers to a tropospheric arrival, O to an ozonospheric arrival and I to the ionospheric arrival. The numbers in parentheses denote the peak-to-peak amplitudes of the recorded pressure waves in *m*bar. The notation (1) denotes no signal-to-noise [Data adopted from *Reed* (1969)].

Station	Wheeler(0.197 KT)	LaPlace(1.0 KT)	John(2 KT)
UCC	T(3200)	T(12600)	(1)
CP-1	T(1710)	T(5600)	(1)
Las Vegas	O(28.6)	T(10) O(52)	(1)
Boulder City	T(1.2) O(41.0)	O(150)	(1)
St. George	O(30)	T(3) O(41) I(14)	2.4
Lund	T(12) O(180)	T(6) O(60) I(6)	(1)
Tonopah	T(123) O(18)	T(15) O(79.5) I(33)	O-(1)
Bishop	T(3.0) O(45) I(15)	T(6) O(240) I(15)	O(5.4)
Inyokern	O(50) I(30)	O(492) I(66)	O-(1)

Table 17. Stations and ranges in km from the NTS for the PLUMBBOB test series conducted during 1957. [Data adopted from *Reed* (1969).]

Station/ Yield	Franklin (0.14 KT)	Lassen (0.47 KT)	John (2.0 KT)	Wheeler (0.197 KT)	LaPlace (1.0 KT)	Ranier (1.7 KT)
CP-1	12.8	22.3	22.7	22.2	17.0	30.93
Las Vegas	125.2	135.9	136.4	136.4	131.1	147.2
Boulder City	159.1	167.1	167.5	167.5	162.4	180.3
St. George	216.2	218.4	217.9	217.9	216.2	237.0
Tonopah	147.4	139.3	139.3	138.9	143.9	142.4
Bishop	213.7	210.0	210.4	210.4	212.7	198.8
Inyokern	210.3	214.8	215.9	215.9	210.3	213.2
Lund			213.0	213.0	217.1	216.6
Coaldale			188.5			
UCC				19.5	14.8	29.0

Table 18. Signal amplitudes recorded from selected low yield explosions detonated in the HARDTACK II test series. In the table, T refers to a tropospheric arrival, O to an ozonospheric arrival and I to the ionospheric arrival. The numbers in parentheses denote the peak-to-peak amplitudes of the recorded pressure waves in *m*bar. The notation (1) denotes no signal-to-noise [Data adopted from *Reed* (1969)].

Station	Eddy(0.083 KT)	Mora(2.0 KT)	Hidalgo(0.077 KT)	Quay(0.079 KT)
UCC	T(3040)		T(2540)	T(3180)
CP-1	T(2588)	T(17500)	T(2640)	T(4250)
FFO		T(6020)		
MOB	T(1880)			
Las Vegas	T(1.2) O(11)	T(210) O(60)	T(18) O(5.8)	O(14)
Boulder City	T(0.8) O(11.8)	T(28) O(50)	T(28.4) O(34)	O(22)
St. George	O(12.8)	O(408)	O(53.4)	T(3.2) O(217.6) I(7)
Bishop	O(66.6)	O(71.4) I(18)	O(6) I(9)	O(4.5)
Inyokern	O(48.6) I(4.8)	T(10) O(176) I(44)	O(6.6) I(29)	O(7)

Table 18 (Cont.). Signal amplitudes recorded from selected low yield explosions detonated in the HARDTACK II test series. In the table, T refers to a tropospheric arrival, O to an ozonospheric arrival and I to the ionospheric arrival. The numbers in parentheses denote the peak-to-peak amplitudes of the recorded pressure waves in *m*bar. The notation (1) denotes no signal-to-noise [Data adopted from *Reed* (1969)].

Station	Lea(0.083 KT)	Hamilton (0.00117 KT)	Donna Anna (0.037 KT)	Rio Arriba(0.079 KT)
CP-1	T(7200)	T(732)	T(4620)	T(2400)
UCC				T(3600)
CP-1M	T(6300)			
Las Vegas	T(10.6) O(59)	O(<1.6) (1)	O(5)	T(4) O(18)
Boulder City	O(102)	O(1)	O(5)	O(33)
St. George	O(344)	O(20)	O(139)	T(6) O(216)
Bishop	O(30.6) I(26.4)	T(2) O(1)	O(<0.3) (1)	O(2) I(13)
Inyokern	O(57) I(18.4)	O(<1) (1)	O(1)	O-(1)

Table 18 (Cont.). Signal amplitudes recorded from selected low yield explosions detonated in the HARDTACK II test series. In the table, T refers to a tropospheric arrival, O to an ozonospheric arrival and I to the ionospheric arrival. The numbers in parentheses denote the peak-to-peak amplitudes of the recorded pressure waves in *m*bar. The notation (1) denotes no signal-to-noise [Data adopted from *Reed* (1969)].

Station	Vesta(0.024 KT)	Wrangell(0.115 KT)	Rushmore(0.077 KT)	Catron(0.021 KT)
BJY	T(630)			
CP-1	T(37)	T(3720)	T(440)	T(3120)
UCC		T(3540)	T(600)	T(4800)
Las Vegas	O(3.6)	T(33) O(9.6)	T(5) O(26)	T(2.7) O(11.5) I(14)
Boulder City	O(11.4)	T(17.4) O(18.6)	T(2) O(92) I(11)	O(21) I(8)
Coyote		T(3540)	T(330)	T(72)
St. George	T(>96)	O(210)	O(220)	O(150)
Bishop	T(12) O(<6) (1)	T(9) I(12)	I(36)	O-(1)
Inyokern	O(3)	O(<4) (1)	O(2)	O-(1)

Table 18 (Cont.). Signal amplitudes recorded from selected low yield explosions detonated in the HARDTACK II test series. In the table, T refers to a tropospheric arrival, O to an ozonospheric arrival and I to the ionospheric arrival. The numbers in parentheses denote the peak-to-peak amplitudes of the recorded pressure waves in *m*bar. The notation (1) denotes no signal-to-noise [Data adopted from *Reed* (1969)].

Station	DeBaca(2.2 KT)	Chavez0.6 KT)
UCC	T(15300)	T(1476)
CP-1	T(10380)	T(1402)
Mercury	T(468)	
Las Vegas	T(15.3) O(78)	O(6) I(2)
Boulder City	O(456)	O(8.7)
St. George	T(348) O(1590)	O(13)
Bishop	O(9) I(72)	O(3.3) I(1.2)
Inyokern	O(9.6) I(55.6)	O-(1)

Table 19. Stations and ranges in km from the NTS for the HARDTACK-II test series conducted during 1957. [Data adopted from *Reed* (1969).]

Station/ Yield	Eddy (0.083 KT)	Mora (2.0 KT)	Hildalgo (0.077 KT)	Quay (0.079 KT)	Lea (1.4 KT)	Hamilton (.0017 KT)	Dona Ana (.037)
UCC	14.2	17.0	14.2	13.3	17.0		
CP-1	16.8		17.0	18.0		18.8	17.0
CP-M1					17.0		
FFO		43.6					
MOB	17.0						
Las Vegas	131.1	131.1	131.1	133.9	131.1	99.4	131.1
Boulder City	162.4	162.4	162.4	163.2	162.1	133.5	162.4
St. George	216.2	216.2	216.2	216.3	216.2	210.8	216.3
Bishop	212.7	212.7	212.7	212.5	212.7	228.2	212.7
Inyokern	213.0	213.0	213.0	213.7	213.0	198.2	213.0

Table 19 (Cont.). Stations and ranges in km from the NTS for the HARDTACK-II test series conducted during 1957. [Data adopted from *Reed* (1969).]

Station/ Yield	Rio Arriba (0.09 KT)	Vesta (0.024 KT)	Wrangell (0.115 KT)	Rushmore (0.133 KT)	Catron (0.021 KT)	DeBaca (2.2 KT)	Chavez (0.6)
UCC	10.0		20.6	19.5	8.3	14.5	10.6
CP-1	12.7	21.3	18.8	22.2	12.74	17.0	12.7
BJY		6.8					
Mercury						47.4	
Coyote			87.8	68.6	65.22		
Las Vegas	127.6	135.9	99.2	136.4	125.2	131.1	125.2
Boulder City	161.3	169.5	133.5	167.5	159.1	162.4	159.1
St. George	216.2	217.6	210.8	217.9	234.5	216.2	216.2
Bishop	213.7	210.6	228.2	210.4	213.7	212.7	213.7
Inyokern	210.3	215.8	198.2	214.2	210.3	213.7	210.3

3.0 THE IMPLICATIONS OF PAST MONITORING EFFORTS ON CURRENT INTERESTS FOR THE CTBT

Although classification restrictions prohibit a listing of all station locations and performance details of the previous monitoring efforts, quite useful information has recently been made available by *Nicholson* (1995) and by investigators at AFTAC [*Clauter and Blandford*, 1996].

Nicholson (1995), in work based on an earlier investigation of the so-called 1979 "Alert 747" event [*Nicholson and Olsen*, 1980], modeled the performance of the USAEDS infrasonic network as measured by probability of detection as a function of the explosive yield and the distance between the test site and receiver location. The work was based on data acquired at 30 stations from 60 explosions of known yield and, accordingly, eliminated any possibility for the inclusion of false alarms. As noted by *Nicholson* (1995), however, the data set of 781 observations was incomplete as not all stations were operational for all of the events: i.e., the total number of possible observations is 1800 (60 x 30). Table 20 provides the number of observations arranged by yield-distance categories.

In analyzing the data set *Nicholson* (1995) applied the statistical analysis procedure known as logit analysis and a maximum likelihood approach developed by *Jennrich and Moore* (1975) to derive a set of curves from which detection probability can be estimated for a given explosive yield and source-to-receiver range. The details of the analysis are not presented herein and only the results of the analysis are provided in Figure 13.

As indicated in the figure, the detection probability is estimated to be a nonlinear function of the logarithm of the source-to-receiver distance and that for 90% probability of detection, the source-to-receiver range should be less than or equal to roughly 800 km and 1300 km for 1 KT and 3 KT explosions respectively.

Distance(Km)	≤10	10 - 100	100 - 1000	≥1000	Total
	Yield (KT)				
1000-1999	37	3	5	2	47
2000-2999	34	*			34
3000-3999	55	2	2	2	61
4000-4999	124	6	6	4	140
5000-5999	123	4	3	1	131
6000-6999	58	8	7	2	75
7000-8999	23	9	12	3	47
9000-10999	40	19	20	5	84
11000-14999	45	22	20	1	88
15000-16999	17	9	19		35
17000-21000	24	9	6		39
TOTAL	580	91	94	20	781

Table 20. The number of atmospheric nuclear explosion events arranged according to yield-distance categories. [Figure adopted from *Nicholson* (1995).]

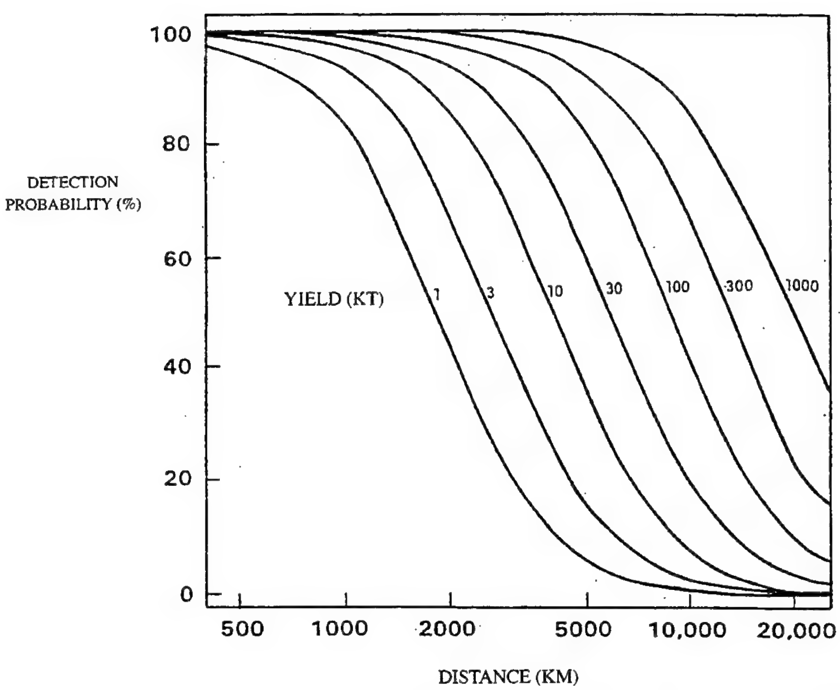


Figure 13. Detection probability as a function of yield and source-to-receiver range based on an analysis of 781 nuclear tests monitored by the USAEDS infrasonic network. [Figure adopted from *Nicholson* (1995).]

In related work, AFTAC has derived a very useful "pressure-range" curve which is provided in Figure 14 and which has been developed by combining AFTAC data from infrasonic measurements of all country atmospheric tests during the 1950's and early 1960's which were in the yield range extending from 0.2 KT to 122 KT and more recent kiloton sized ANFO (ammonium nitrate and fuel oil) chemical surface explosions detonated in the continental U.S. The amplitudes of the ANFO explosions were less than 6 KT nuclear equivalent.

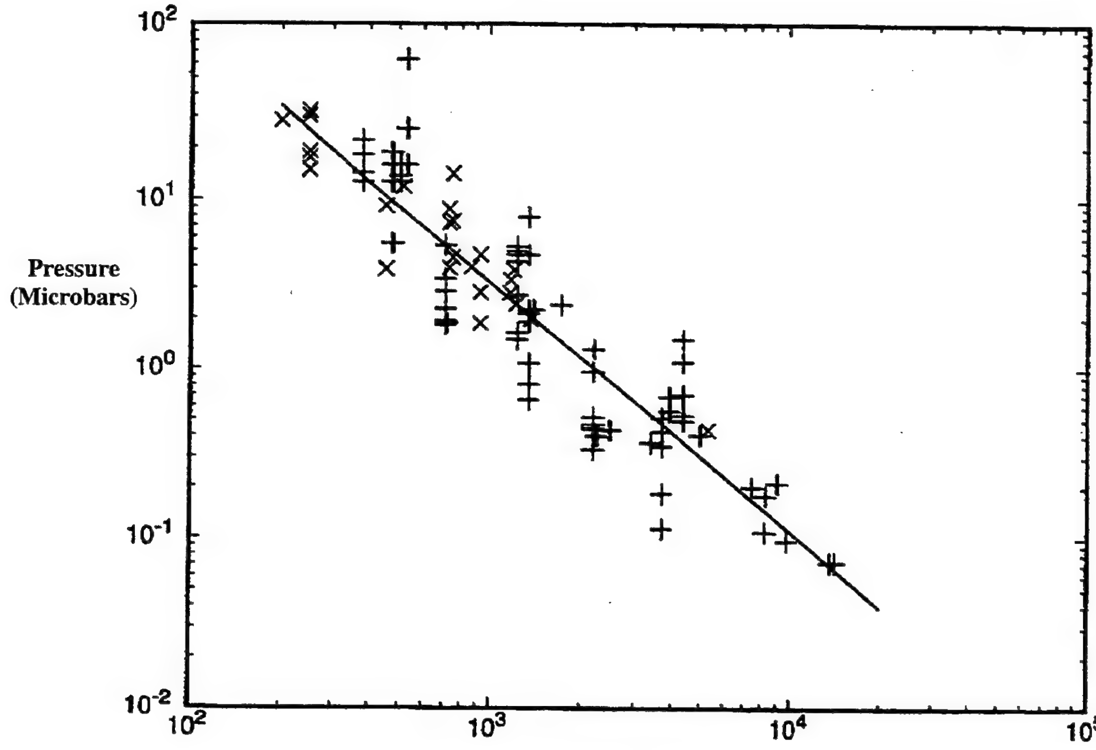


Figure 14. The pressure-range curve developed by AFTAC which was constructed from past infrasonic measurements of pressure waves from atmospheric nuclear explosions. The figure is based on square root scaling of yield to 1 KT and the +'s refer to nuclear explosions and the X's refer to ANFO data. [Figure provided by AFTAC {*Clauter and Blandford* (1996)}].

To account for the different nuclear source yields, the observed zero-to-peak (not peak-to-peak) pressure amplitudes were normalized to 1 KT by dividing the pressure amplitudes by the square root of the yield. For the ANFO recordings, a yield of 0.62 KT was assumed to be equivalent to 1 KT nuclear yield. As indicated in the figure, the

logarithm of the scaled zero-to-peak amplitudes is linear with the logarithm of the source-to- receiver range in km. The equation for the best least-squares fit to the data is given by

$$\mathrm{Log}_{10}(P) = 1.92 + 0.5\,\mathrm{Log}_{10}(Y) - 1.47\,\mathrm{Log}_{10}(D) \qquad (4.1)$$

where P is the pressure in μbar, Y is the explosive yield in KT and D is the source-to-receiver range in degrees.

In addition to the pressure-range curve, AFTAC has also constructed an empirical single sensor noise curve which allows an estimation of sensor noise level in μbar given the local wind speed in knots. The noise curve is shown in Figure 15 and was derived by combining actual measured average annual and monthly noise levels in μbar from former operational stations with known annual and monthly average wind speed values available from the unclassified literature for meteorological stations near the infrasound measurement sites. As indicated in the figure, the noise level is predicted to be a quadratically increasing function of the wind speed. Also, as noted by *Clauter and Blandford* (1996), the best-fit curve to the data implies a fundamental noise floor of 0.3 μbar. In the figure, the circles

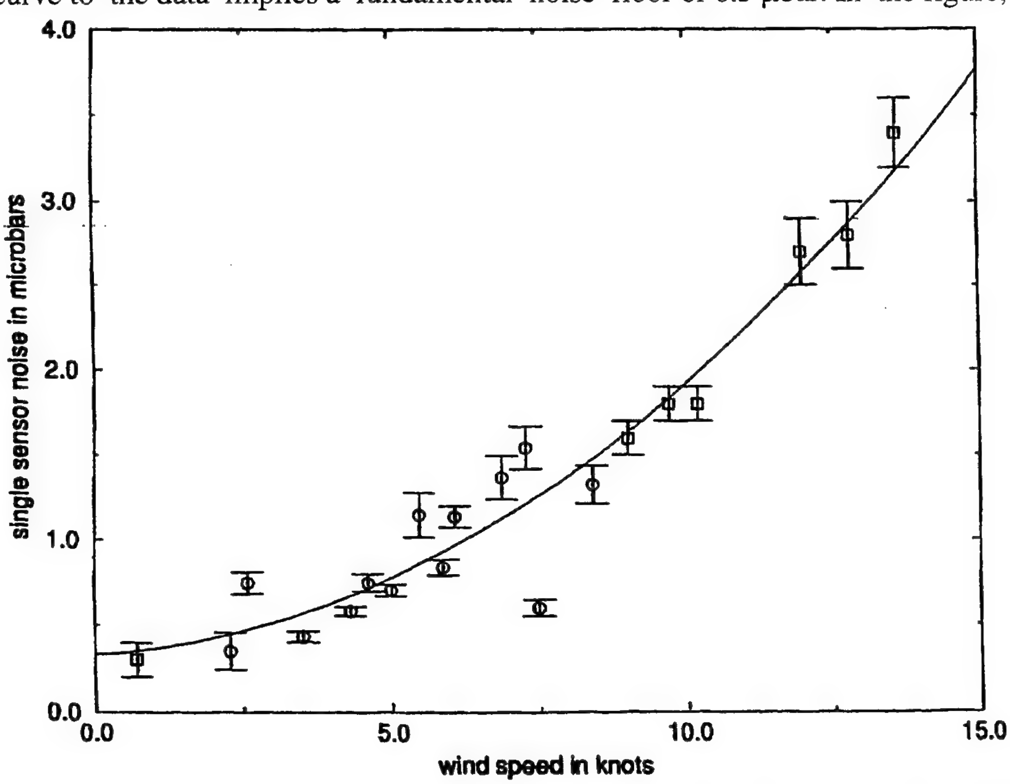


Figure 15. Single sensor noise levels in μbar as a function of wind speed in knots. [Figure provided by AFTAC {*Clauter and Blandford* (1996)}].

represent the yearly means and the brackets the variability as measured by $\pm$ one standard deviation.

Given the pressure-range and sensor noise curves, *Clauter and Blandford* (1996) utilized the "NETSIM" network performance program developed for use in the seismic community to compute magnitude detection probability contours for networks of arbitrary design and numbers of elements. The calculations assume that the signal and noise amplitudes are log-normally distributed and the probability of detection is assumed to be of the form

$$P_{ijk} = R_i \, \Phi\left[\frac{\mathrm{Log}_{10}(S_{ijk}) - \mathrm{Log}_{10}(N_{ijk}) - \mathrm{Log}_{10}(SNR_{ijk})}{\left(\sigma^2_{S_{ijk}} + \sigma^2_{N_{ijk}}\right)^{1/2}}\right] \qquad (4.2)$$

where in the above, P is the probability of detection at the i-th station, for the j-th source location and the k-th event, R_i is the reliability of the i-th station (assumed to be 95%), S is the signal amplitude, N is the noise amplitude, SNR is the signal-to-noise ratio required for a detection (assumed to be 1.5), σ_S and σ_N are the log standard deviations of the signal and noise, respectively, and Φ is the well known normal probability function.

Given the assumed detection model, and taking the log standard deviations of the signal and noise each to be equal to 0.3 (based on empirical operational data), the predicted magnitude-probability performance of the 60 element station under consideration for CTBT monitoring is provided in Figure 16. The triangles in the figure represent the assumed station locations and the yield-contours represent the minimum detectable yield if a 90% probability of detection is required by at least two stations in the network. The figure clearly illustrates that monitoring at the 1 KT level is feasible and, because of higher station density, that yield estimation is better in the northern than in the summer hemisphere and that detection is better over land than over water. For comparison purposes, Figure 17 provides the results of the same calculations for an assumed 50 element network and comparison between Figures 16 and 17 illustrates the rather significant detection improvement achieved by utilizing a larger number of stations.

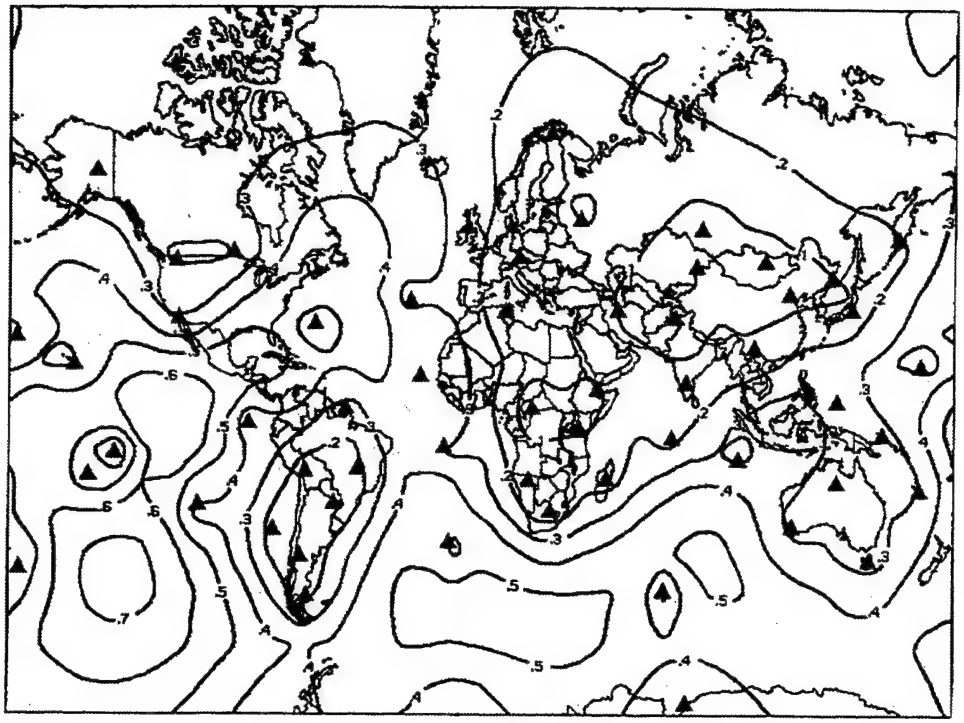


Figure 16. Magnitude-probability contours for a proposed 60 station CTBT infrasonic monitoring network. Station locations are shown by the solid triangles and the contours represent detectable yields under the requirement that there be a 90% probability of detection by at least two stations. [Figure adopted from *Clauter and Blandford* (1996).]

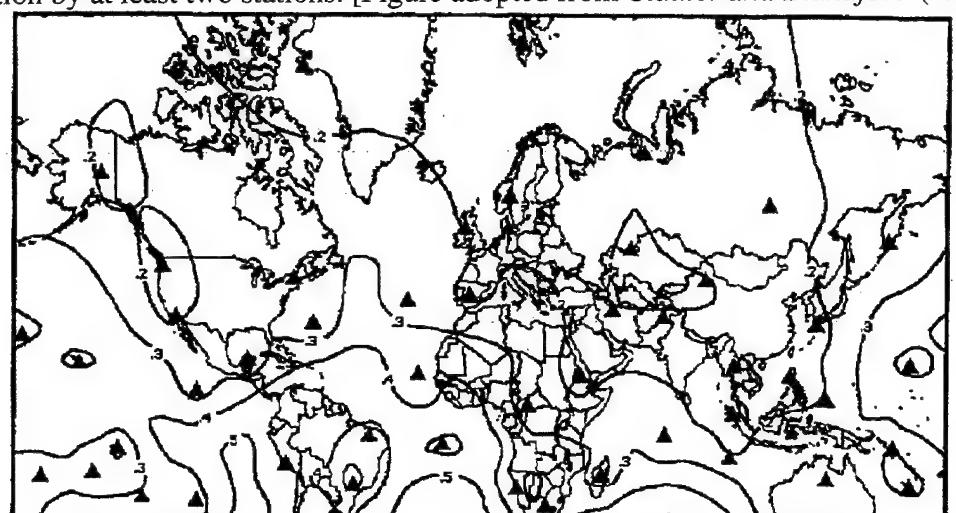


Figure 17. Magnitude-probability contours for a proposed 50 station CTBT infrasonic monitoring network. Station locations are shown by the solid triangles and the contours represent detectable yields under the requirement that there be a 90% probability of detection by at least two stations. [Figure adopted from *Clauter and Blandford* (1996).]

In addition to the foregoing, *Clauter and Blandford* (1966) have also modeled location uncertainty utilizing the model assumed for probability of detection (Eq 4.2) and the measured standard deviations for the speed of signal propagation and azimuthal uncertainties. The location uncertainty was quantified in terms of the radius of uncertainty circle under various different assumptions, e.g.; (1) travel time data not considered; (2) a 5% uncertainty in the travel time; (3) a 2% uncertainty in the speed of signal propagation. For purposes of illustration, Figure 18 presents location uncertainty results for the 60 station network under the assumption a 2% uncertainty in signal travel speed. As indicated in the figure, the radius of uncertainty is approximately 100 km over most ocean areas and approximately 225 km in the worst case.

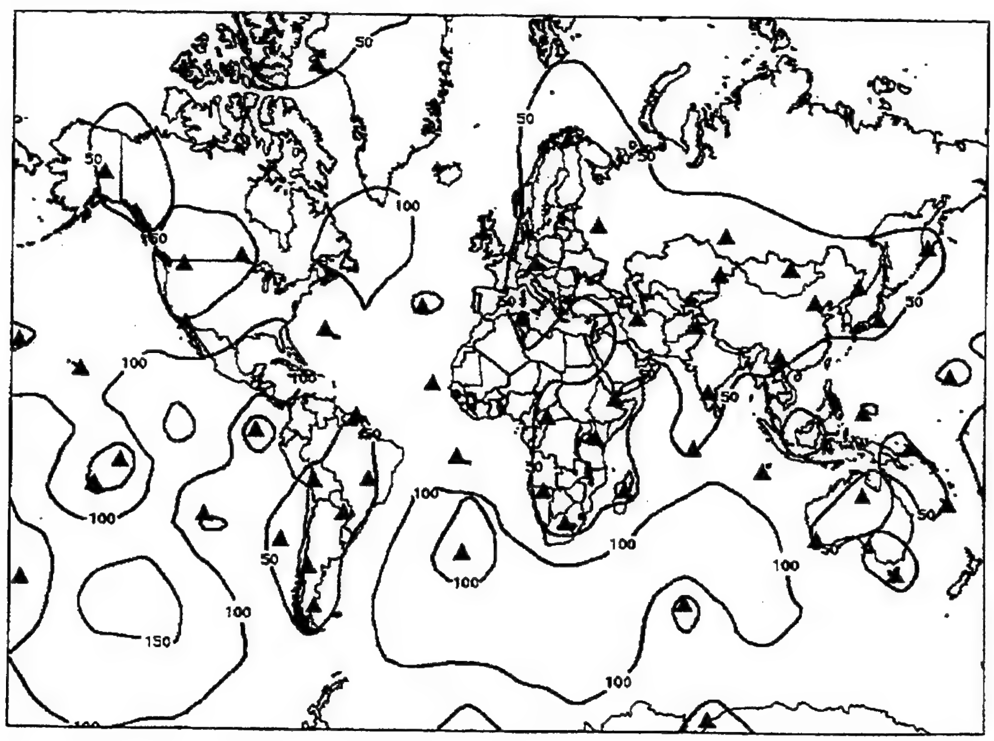


Figure 18. Radius of circle uncertainty contours for a 60 station infrasound network under the assumption of a 2% uncertainty in measured signal speed from the source to the receiver. [Figure adopted from *Clauter and Blandford* (1996).]

4.0 DISCUSSION OF RESULTS

In the foregoing sections previous unclassified work dealing with the monitoring of atmospheric nuclear explosions in the low-yield range of current interest to the monitoring of a CTBT was reviewed. The detection performance of continental stations used to monitor U.S. tests at the NTS indicates that maximum detection ranges for explosions of 1 KT can vary from 1350 km to 3585 km depending on the noise levels at a particular station and on the environmental conditions along the propagation path.

The modeling work of *Nicholson* (1995), which was based on the utilization of 781 explosions recorded on the entire USAEDS system would seem, at first glance, to suggest significantly shorter ranges: e.g., 800 km and 1300 km for 1 KT and 3 KT yield explosions, respectively. However, it is important to keep in mind that the empirical probability of detection curves were derived by averaging over a significant amount of data and may not, accordingly, be representative of detection ranges which could be achieved under the most favorable conditions.

The modeling work of *Clauter and Blandford* (1996), also based on the utilization of data from the entire USAEDS system, suggests that a proposed 60 station infrasound network can ensure detection at the 1 KT level with a location uncertainty of 100 km, particularly if some of the four-element southern ocean stations are augmented with additional stations to increase array gain. Given that the average station separation of the proposed 60 element network is between 2000 km to 3000 km, it appears that the results of *Clauter and Blandford* (1996) are in accord with the independent estimates of *Christie* (1995) [not presented herein] suggesting that station spacing should not exceed 2500 km.

At project inception, it is parenthetically noted, the author was under the erroneous assumption that the previously described programs involved with the monitoring of atmospheric nuclear explosions were part of the well known VELA Program. In particular, it was believed that the overall VELA effort was comprised of several categories or "compartments" each of which was associated with a particular technology utilized by the

program. For example, under VELA was the VELA Uniform segment which is exclusively associated with the seismic monitoring effort [*Kerr,* 1985] directed toward the monitoring of underground nuclear explosions. There were other compartments as well such as VELA HOTEL and VELA SIERRA. As a result of the review, it has been established that VELA HOTEL was associated with satellite monitoring and that VELA SIERRA was associated with hydroacoustic monitoring. In fact, there was no compartment of VELA associated with infrasonic monitoring *per se* and, indeed, the origins of infrasonic monitoring significantly predate the establishment of the VELA Program. Said another way, infrasonic monitoring was indeed a part of the VELA program but was not accorded a separate compartment.

The VELA Program originated in 1958 at the time of the Geneva Conference of Expert's discussions on the discontinuance of nuclear testing and, indeed, at this time it was recognized that extant acoustic (or infrasonic) techniques worked and were well understood.

With the advent of rockets, it was realized that tests in the upper atmosphere and space were both feasible and probable. In fact, the first U.S. nuclear tests in the upper atmosphere were conducted at about the time of the "Geneva Conference of Experts to Study the Methods of Detecting Violations of Possible Agreement on the Suspension of Nuclear Tests". The conference of experts recognized that the detection of a burst above the atmosphere must involve techniques that are, on the whole, different from those used for atmospheric bursts. The 1958 Conference directed that a more detailed study of the problem be made by a Technical Working Group [the so-called "Panofsky Panel"]. The conference of experts also, evidently, established another Technical Working Group which focused on improving seismic monitoring [the so-called Berkner Panel"].

The recommendations of the "Panofsky Panel" provided for the establishment of that portion of the VELA research program which was directed toward the detection of upper atmospheric and space tests of nuclear weapons. The VELA Program , however,

also incorporated other research directed toward the detection of tests at lower altitudes as well as underwater.

Romney (1985) places the birth of the VELA Program as April 23, 1959 during a meeting between President Kennedy's Special Assistant for Science and Technology (Dr Killian), the Atomic Energy Commission Chairman (Mr. McCone) and the Deputy Secretary of Defense (Mr. Quales) which "decided to implement the programs of research recommended by these panels for improving national capabilities to detect and identify foreign nuclear explosions conducted in the two difficult (upper atmospheric and underground) environments." The name "VELA" (or "vigilance") Program evidently occurred when the "Secretary of Defense assigned responsibility to the Advanced Research Projects Agency."

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Gerald Afflerback
ASC
Detachment 3, 1031 S. Hwy. A1A
Patrick AFB, FL 32925
USA

Don Albert
U.S. Army, CRREL
72 Lyme Road
Hanover, NH 03755-1290USA

Terrance Barker
Maxwell Technologies
8888 Balboa Ave.
San Diego, CA 92123
USA

Jonathan Berger
IGPP/SIO
9500 Gilman Dr.
La Jolla, CA 92093-0225
USA

Robert Blandford
AFTAC
Suite 1450, 1300 N17th St.
Arlington, VA 22209
USA

David Brown
Australian National University
Research School of Earth Sciences
Canberra, ACT 0200
Australia

Edwin Bullard
Chaparral Physics Consultants
7405 Capulin Road NE
Albuquerque, NM 87109
USA

Leslie Casey
U.S. Department of Energy
NN-20, 1000 Independence Av., SW
Washington, DC 20585-0420
USA

Douglas Christie
Provisional Technical Secretariat, CTBTO
Vienna Int'l. Center, P.O. Box 1200
Vienna, A-1400
Austria

Pierce Corden
Arms Control and Disarmament Agency
3020 21st St. NW, Rm. 5499, MA/NTP
Washington, DC 20451
USA

Haydar Al-Shukri
ENSCO Inc.
445 Pineda Court
Melborne, FL 32940
USA

William Armstrong
Los Alamos National Laboratory
EES-8, MS F659
Los Alamos, NM 87545
USA

Al Bedard
NOAA, Environmental Tech. Laboratory
Mail Code R/E/ET4 325 Broadway
Boulder, CO 80303-3328
USA

Elisabeth Blanc
Commissariat A L'Energie Atomique
Laboratoire de Detection et de Geophysique BP 12,
Bruyères le Chatel, 91680
France

Dale Breding
Sandia National Laboratories
MS 0979, Org. 5704
Albuquerque, NM 87185
USA

Wendee Brunish
Los Alamos National Laboratory
EES-DO, MS F659
Los Alamos, NM 87545
USA

Peter Cable
BBN Systems and Technologies
Union Station
New London, CT 06320
USA

Luis Cella
Autoridad Regulatoria Nuclear (ARN)
Av.del Libertador 8250
Buenos Aires 1429,
Argentina

Dean Clauter
HQ AFTAC/TTR
1030 South Highway A1A
Patrick AFB, FL 32925-3002
USA

Ola Dahlman
Vienna International Center
P.O Box 1200
Vienna A-1400,
Austria

Kalpak Dighe
Los Alamos National Laboratory
PO Box 1663, MS C300
Los Alamos, NM 87545
USA

Pierre-Andre Duperrex
Defense Procurement Agency
FS 161 Stauffacherstrasse 65
3000 Bern 22,
Switzerland

Milton Garcés
University of Alaska
903 Koyukuk Dr., P.O Box 757320
Fairbanks, AK 99775-7320USA

Robert Gibson
BBN Corporation
1300 N. 17th St., Suite 1200
Arlington, VA 22209
USA

Georgui Golitysn
Institute of Physics of the Atmosphere RAS
3 Pyshevsky
Moscow, 109017
Russia

Gerhard Graham
Council for Geoscience
Private Bag X112
Pretoria, 0001
South Africa

K. Guthrie
Defense Scientific Establishment
Private Bag 3290
Auckland,
New Zealand

Heinrich Haak
Royal Netherlands Meteorological Institute
Seismology Division, P.O. Box 201
DeBilt, 3730 AE
Netherlands

Vincent Harman
ASC/RAKBS
Building 557 2640 Loop Road West
Wright Patterson AFB, OH 45433-7607

Gernot Hartmann
BGR Hannover
Postfach 510153
30631 Hannover,
Germany

David Havelock
National Research Council Canada
M-36 Montreal Road
Ottowa, ONT K1A OR6
Canada

Michael Hedlin
University of California San Diego
9500 Gilman Drive
La Jolla, CA 92093-0225
USA

Eugene Herrin
Southern Methodist University
P.O Box 395, SMU Dept of Geology
Dallas, TX 75275
USA

Preston Herrington
Sandia National Laboratories
P.O Box 5800, MS 0655
Albuquerque, NM 87185-0655
USA

Mark Hodgson
Los Alamos National Laboratory
MS D460
Los Alamos, NM 87545
USA

Wolfgang Hoffmann
Vienna International Centre
P.O Box 1200, Room E0754
Vienna A-1400,
Austria

James Hunter, Jr.
University of Florida
414 NE 6th St.
Gainesville, FL 32601
USA

Kevin Hutchenson
ENSCO Inc.
445 Pineda Court
Melbourne, FL 32940
USA

Rong-Song Jih
Defense Special Weapons Agency
HQ DSWA/PMP, 6801 Telegraph Road
Alexandria, VA 22310
USA

Charles Katz
Science Applications International Corporation
10260 Campus Point Drive
San Diego, CA 92121
USA

Robert Kemerait
HQ/AFTAC
AFTAC/TT, 1930 Highway A1A
Patrick AFB, FL 32925
USA

Richard Kromer
Sandia National Laboratories
MS 0655
Albuquerque, NM 87185
USA

Sergey Kulichkov
Institute of Atmospheric Physics
3 Pyzevsky
Moscow, 109017Russia

Ludwik Liszka
Swedish Institute of Space Physics
Sorfors 634
UMEA, S-90588
Sweden

Peter Marshall
Ministry of Defense
Blacknest/Brimpton
Reading F67-4RS,
UK

Bernard Massinon
Laboratoire de Detection et de Geophysique
Centre de Bruyeres-le-Chatel BP 12
Bruyères le Chatel, 91680
France

David McCormack
Geological Survey of Canada
1 Observatory Crescent
Ottowa, ONT KIA 0Y3
Canada

J. Michael McKisic
TRACOR Applied Sciences
1601 Research Boulevard
Rockville, MD 20850-3191
USA

Richard Morrow
U.S. Arms Control and Disarmament Agency
320 21St.
Washington, DC 20451
USA

Philip Munro
Geological Survey of Canada
1 Observatory Crescent
Ottowa, ONT KIA 0Y3
Canada

Timothy Murphy
ACIS
7105 Norwalk St.
Falls Church, VA 22043
USA

Joseph Mutschlecner
Los Alamos National Laboratory
121 Sierra Vista
Los Alamos, NM 87544
USA

Vladimir Ostashev
New Mexico State University
Department of Physics, Box 30001 / Dept. 3D
Las Cruces, NM 88003-8001
USA

Frank Pilotte
AFTAC/TT
1030 South Highway A1A
Patrick AFB, FL 32925-3002
USA

Oleg Raspopov
Russian Academy of Sciences
Terrestrial Magnetism, Ionsphere and Radio Waves Prop., Box 188
St. Petersburg, 191023 Russia
Russia

Terrill Ray
U.S Arms Control and Disarmament Agency
320 21st. Street NW
Washington, DC 20451
USA

Douglas Revelle
Los Alamos National Laboratory
P.O. Box 1663, MS F659
Los Alamos, NM 87545
USA

Jose Roca
Autoridad Regulatoria Nuclear (ARN)
Av. del Libertador 8250
Buenos Aires 1429,
Argentina

David Russell
HQ/AFTAC/TTR
Air Force Tech. Applications Center 1030 S. Highway A-1A
Patrick AFB, FL 32925-3002
USA

Tom Sandoval
Bechtel/Nevada
P.O Box 809
Los Alamos, NM 87544
USA

David Simons
Los Alamos National Laboratory
PO Box 1663, MS D460
Los Alamos, NM 87545
USA

Eugene Smart
HQ/AFTAC/TTR
Air Force Tech. Applications Center 1030 S. Highway A-1A
Patrick AFB, FL 32925-3002
USA

Warwick Smith
Institute of Geological and Nuclear Science
P.O. Box 30-368
Lower Hutt, New Zealand

David Spell
609 Chena Ridge Road
Fairbanks, AK 99709
USA

Bruno Stork
Fed. Inst. for Geosciences and Natural Res.
Stilleweg 2
Hannover, 30655
Germany

Alexander Sytolenko
Cabinet of Ministers of Ukraine
Chief, National Space Agency of Ukraine, M. Hrushevsky St., 12/2
Kyjiv-002,
Ukraine

Vladimir Timofeev
Cabinet of Ministers of Ukraine
Deputy Chief, Dept. on Issues of Technology, Ecology, Safety and Civil Protection M. Hrushevsky St.,12/2
Kyjiv-002,
Ukraine

Lawrence Trost
Sandia National Laboratories
Org. 5415, MS-0425, Sandia National Laboratories
Albuquerque, NM 87185
USA

Alberto Veloso
Preparatory Commission for CTBTO
P.O Box 1250
Vienna A-1400,
Austria

Robert Waldron
Department of Energy
NN-20 1000 Independence Ave. SW
Washington, DC 20585-0420
USA

Joseph Wheeler
Boeing Company
PO Box 21233
Kennedy Space Center, FL 32813
USA

Rodney Whitaker
Los Alamos National Laboratory
EES-8 MS F659
Los Alamos, NM 87545
USA

Raymond Willemann
Center for Monitoring Research
1300 North 17th Street, Suite 1450
Arlington, VA 22209
USA

Charles Wilson
University of Alaska
Geophysical Institute, 1812 Musk Ox Trail
Fairbanks, AK 99709
USA

Jin Lai Xie
Chinese Academy of Sciences
Institute of Acoustics, P.O Box 2712
Beijing 100080,
China

Zhao Hua Xie
Chinese Academy of Sciences
Computer Network Info. Ctr, P.O Box 2719
Beijing 100080,
China